AD-A271 751

US Army Corps
of Engineers
Construction Engineering
Research Laboratories

USACERL Technical Report FM-93/04
April 1993
Integrated Base Isolation/Building System Evaluation

Design of a Tridirectional Reaction Frame for Comparative Dynamic Testing of Base Isolation Systems

by
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This report presents the results of review, analysis, and design work addressing the development of a reaction frame for tridirectional testing of base isolation assemblies and a detailed program for the comparative testing of base isolation systems. This first phase of a multiphase research program produced documentation of a reaction frame for the three-dimensional dynamic testing of 1/3 to 1/2 scale seismic isolation units. Factors limiting the scale of the isolation units were (1) the capacity of existing servo-hydraulic actuators at the proposed test site and (2) the capacity of the site's hydraulic systems.

The proposed testing program would thoroughly investigate the tridirectional behavior of several base isolation systems. Characteristics to be evaluated and compared would include frequency dependence, stiffness as a function of shear strain, energy dissipation as a function of shear and axial strain, and isolator stability as a function of axial force and shear strain. The program would also use a 1,000 kip compression/tension testing machine to investigate the tensile strength of elastomeric isolators and the vertical energy dissipation characteristics of the various isolation systems at high levels of axial strain.

The final design of the isolation units will be addressed during the next phase of the research program.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1993	Final

4. TITLE AND SUBTITLE

Design of a Tridirectional Reaction Frame for Comparative Dynamic Testing of Base Isolation Systems

5. FUNDING NUMBERS

PE 4A162784
PR AT41
WU MA-CWO

6. AUTHOR(S)

Roland S. Sharpe, Andrew S. Whittaker, and Vahid Sattary

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Construction Engineering Research Laboratories (USACERL)
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER

TR FM-93/04

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Corps of Engineers (HQUSACE)
ATTN: CEMP-ET
20 Massachusetts Avenue NW
Washington DC 20001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS

Base islation systems
reaction frame
Servo-hydraulic actuators
tridirectional reaction frame
earthquake hazard mitigation engineering

15. NUMBER OF PAGES

54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This research was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit MA-CW0, "Integrated Base Isolation/Building Systems Evaluation." The HQUSACE technical monitor was Charles Gutberlet, Jr., CEMP-ET.

The work was performed under contract by Forell/Elsesser Engineers, Inc., San Francisco, for the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). Roland Sharpe, Dr. Andrew Whittaker, and Dr. Vahid Sattary are employees of Forrell/Elsesser Engineers. The authors acknowledge the assistance of the following people in the preparation of this report: John R. Hayes, Jr., Pamalee A. Brady, and James B. Gambill, CECER-FME, for general consultation; and Maurice Gunderson of Edison Systems Corp. for advice on the design and implementation of servo-actuator systems. Dr. Paul A. Howdyshell is Chief, CECER-FM. Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

While earthquakes may seem to be a concern relatively remote from the everyday operations of the U.S. Army, earthquake damage to structures on Army installations is a continuing potential cause of widespread property destruction and personal injury. Ongoing research by the U.S. Army Construction Engineering Research Laboratories (USACERL) addresses this issue by investigating ways to mitigate the hazards arising from earthquakes.

Earthquake hazard mitigation engineering attempts to equate a building's capacity (SUPPLY) to the seismic demands placed on the building by the design earthquake (DEMAND). Engineers seek to ensure the relationship expressed in Equation 1:

$$\text{SUPPLY} \geq \text{DEMAND} \qquad \text{[Eq 1]}$$

Conventional solutions for earthquake hazard mitigation deal only with the left side of the equation—providing enough SUPPLY to exceed DEMAND. Base isolation techniques, on the other, hand operate on both sides of the equation by (1) reducing seismic DEMAND by uncoupling the building from the damaging effects of the severe, high-frequency earthquake shaking, and (2) increasing the building's SUPPLY (or capacity) by increasing its level of hysteretic damping.

Base isolation is growing in popularity as a tool for the seismic design of buildings and other structures. The implementation of base isolation for seismic applications has been advanced by the development and testing of dependable isolation systems and the development of computerized analytical methods for evaluating the behavior of isolated structures. Base isolation has been considered the most effective alternative for seismic upgrading of the Hays Army Hospital at Fort Ord, CA.

Static and dynamic testing of base isolation systems have been conducted in the United States, New Zealand, and Japan for more than a decade. Most of the testing has been sponsored by private-sector firms, and all of it has been bidirectional in nature—vertical and one horizontal direction. Little attempt has been made to comparatively test the different isolation systems available, and no tridirectional testing (vertical and two orthogonal horizontal directions) has been conducted. Consequently, there are no comparative test data available for the engineering profession to judge the effectiveness and applicability of the different isolation systems for tridirectional response to earthquake shaking. To facilitate the use of base isolation systems in the seismic upgrading of Army facilities, specifications must be developed to allow competitive bidding, thereby ensuring an open procurement process for such systems. Comparative tridirectional data are required to develop a performance specification against which any system may compete.

To date, tridirectional isolator response characteristics have been inferred from bidirectional test results. Equivalent viscous damping ratios and bearing roll-out values in the orthogonal horizontal directions have been assumed to be independent. Although this might be a reasonable assumption for circular isolators, there is little justification for applying the same assumption to square or rectangular bearings.

A key reason tridirectional testing of isolation systems has not been undertaken is the lack of an appropriate reaction frame. A well coordinated research program using a tridirectional reaction frame could resolve most of the questions relating to tridirectional behavior of isolation systems.

Objectives

This report documents development of a design for a tridirectional reaction frame for the comparative testing of base isolation systems.

The work reported here comprises the first part of Phase 1 of a three-phase research program. The overall objectives of this research program are the following:

- Phase 1—Testing. Develop a database of test results for use in comparing the response of different isolation systems

- Phase 2—Analysis. Conduct analytical studies of the behavior of different base isolation systems, using constitutive models developed in Phase 1

- Phase 3—Specifications. Prepare specifications, guidelines, and construction details to aid the engineering profession with the implementation of base isolation systems.

Approach

Phase 1 of this three-phase research program includes the following:

1. Design, documentation, and construction of a reaction frame for tridirectional dynamic testing of third- and half-scale isolation units. (This report addresses the design and documentation stage of development of the reaction frame.)

2. Development and performance of a detailed comparative testing program that will investigate isolator behavior under different loading environments.

3. Reduction of the data acquired during the testing program and preparation of a detailed research report that will include a chapter on comparative isolator responses.

This report presents the design and documentation of the reaction frame, and discusses development of a detailed testing program.

Scope

A number of major seismic isolation issues have not yet been resolved. These issues are listed in Table 1.1, and will be addressed in the research phase or phases noted.

Table 1.1

Seismic Isolation Issues

Significant Seismic Isolation Issues	Study Method
1. SYSTEM ACCEPTANCE CRITERIA	
A. Performance	A. Specifications/Testing
B. Testing	B. Testing
C. Durability	C. Testing
D. Physical Configuration (size, shape, etc.)	D. Specifications
2. EARTHQUAKE RESPONSE	
A. Earthquake Ground Motion	A. Analysis
B. Far-Field Resonance	B. Analysis
C. Near-Field Effects	C. Analysis
3. FACTORS OF SAFETY	
A. Vertical Load Combinations	A. Testing
B. Torsion Effects	B. Testing
4. CONFIGURATIONS	
A. Modified Response By Tuning of Isolators	A. Analysis
B. Torsion Effects	B. Analysis
C. Overturning and Uplift Limits	C. Analysis/Testing
D. Diaphragm Flexibility Limits	D. Analysis
E. Friction Effects	E. Analysis
5. BASE ISOLATOR INSTALLATION	
A. Position of Isolators within the Structural System	A. Analysis
B. Mounting Details	B. Testing/Specifications
6. ISOLATOR AND FAIL-SAFE COMBINATIONS	
A. Combination of Isolator and Fail-Safe Systems	A. Testing
B. Impact Forces	B. Testing
C. Uniformity of Performance - Various Systems	C. Testing
D. Installation Requirements and Details	D. Specifications
E. Performance Specifications	E. Specifications
F. Effective Damping	F. Testing/Specifications
7. DESIGN	
A. Criteria and Specifications	A. Specifications
B. Guidelines and Aids	B. Specifications

Mode of Technology Transfer

Upon completion of the overall research program, performance specifications, guidelines, and construction details to aid the Army in implementing base isolation technology will be integrated into existing Army Technical Manuals and Engineer Technical Letters as needed.

2 DESIGN OF THE PROTOTYPE ISOLATORS

Design of the Full-Scale Prototype Buildings

Low- and midrise buildings are ideally suited for seismic isolation systems. Therefore a five-story concrete building and a three-story steel building were chosen as the prototypes for this study.

The concrete building was assumed to have a typical bay size of 24 ft x 24 ft, a floor-to-floor height of 14 ft, a typical floor weight of 190 psf (160 psf reactive) and a roof weight of 140 psf (130 psf reactive).* A typical interior column load (with live load reduction) is 630 kips.**

The steel building was assumed to have a typical bay size of 28 ft x 28 ft, a floor-to-floor height of 13 ft, a typical floor weight of 155 psf (125 psf reactive) and a roof weight of 125 psf (95 psf reactive). For this building, the typical interior column load (with live load reduction) is 460 kips.

Design of the Full-Scale Prototype Isolators

For the preliminary sizing of the isolators, the following specifications were used:

- Target isolation period = 2.5 seconds
- Equivalent viscous damping = 12 percent
- Spectral Acceleration = 0.2g (design-basis earthquake [DBE])
  = 0.3g (maximum credible earthquake [MCE])
- Axial stress limit = 1000 psi (DL+LL)
- Maximum shear strain (DBE) = 100 percent
- Maximum shear strain (MCE) = 150 percent.

The building mass was calculated using relative weights.

The design of the full scale isolators shown in Figure 2.1 was based on using high-damping rubber bearings compounded with LTV 246-70 rubber. The 246-70 compound has a shear stiffness of approximately 155 psi at 100 percent shear strain. A 0.5 in. layer of sacrificial rubber was assumed to provide sufficient protection from the environment.

The components for the typical full-scale isolators are listed in Table 2.1.

*U.S. standard units of measure are used in this report. A table of metric conversion factors can be found on p 37.

**kip: kilopound.

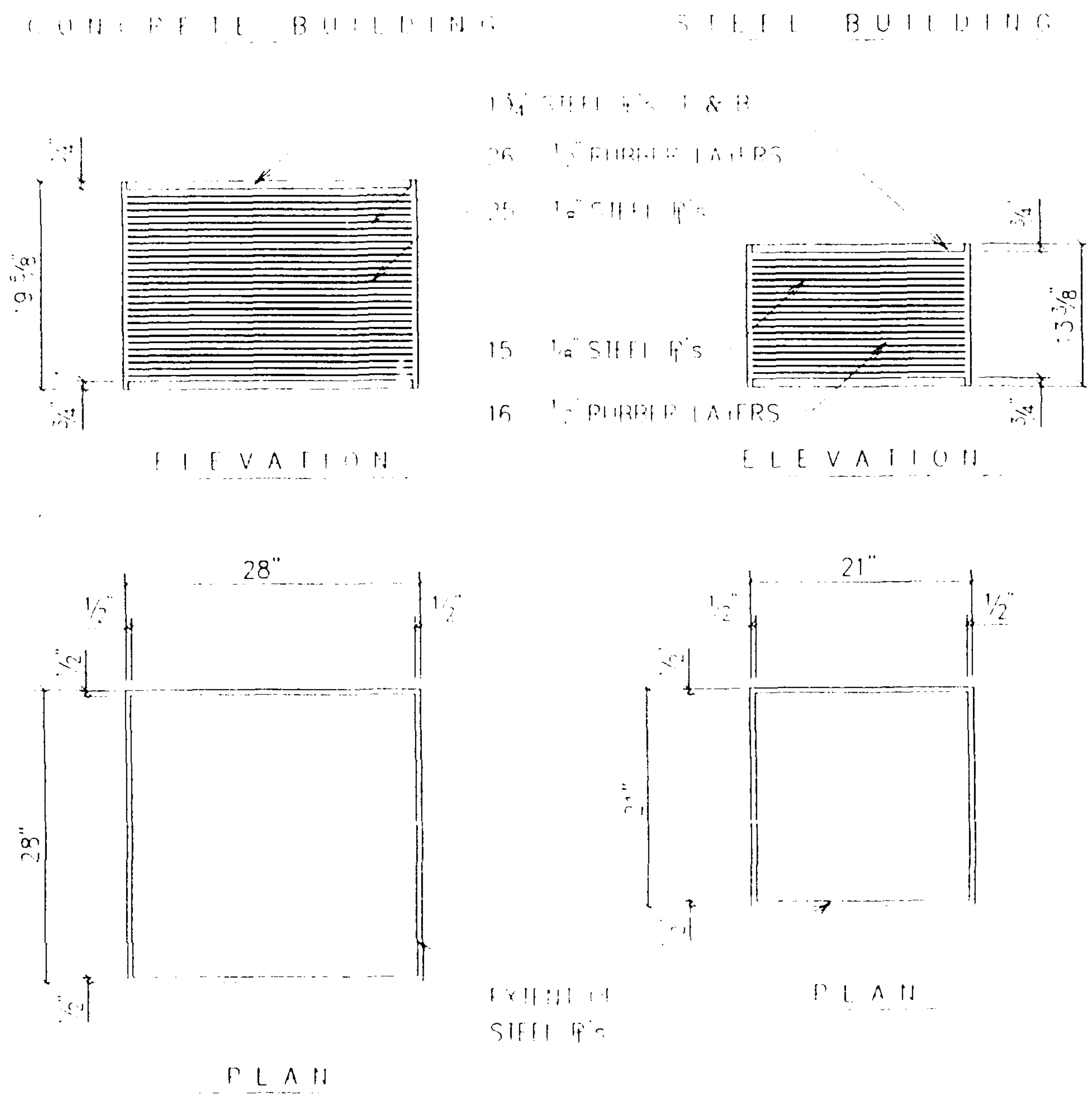

Figure 2.1. Dimensions of Prototype Isolators.

Table 2.1

Components of Full-Scale Isolators

Internal Dimensions

Concrete Building	Steel Building
26, 1/2" thick rubber layers (27" x 27" bonded plan dimension)	16, 1/2" thick rubber layers (20" x 20" bonded plan dimension)
25, 1/8" thick steel shims	15, 1/8" thick steel shims
2, 1 3/4" thick steel end plates	2, 1 3/4" thick steel end plates

*External Dimensions**

28" x 28" x 19-5/8" (high)	21" x 21" x 13-3/8" (high)

* Including 0.5 in. layer of sacrificial rubber.

3 DESIGN OF MODEL ISOLATORS

Similitude Requirements

For the model isolators to be true scaled replicas of the prototype (full-scale) isolators designed and documented in Chapter 2, the laws of similitude must be followed. The geometric similitude laws as they apply to basic response parameters are listed in Table 3.1.

Geometric Parameters Affecting Isolator Response

Six important factors influence the response of elastomeric isolators: stress (axial and shear), strain (axial and shear), stiffness (axial and shear), shape factor, buckling load, and roll-out load. The similitude laws as they apply to these bearing response parameters are listed in Table 3.2.

Design of the Model Isolators

For the design of the model isolators, the parameters of stress, strain, and shape factor were held constant. The shape factor affects the compression stiffness (k_A) and the buckling load (P_B) as follows:

$$k_A = \frac{EA\ (1+1.3A^2)}{t_r} \qquad \text{[Eq 2]}$$

$$P_B = \frac{1.171\ d^3\ G\ S\ (t_r+t_s)}{ht_r} \qquad \text{[Eq 3]}$$

where E is the elastic modulus, A is the bonded plan area of the isolator ($=d^2$), t_r is the thickness of one layer of rubber, t_s is the thickness of a steel shim plate, d is the side dimension (of a square isolator), G is the shear modulus, S is the shape factor, and h is the height between the end-plates. The similitude laws for bearing, buckling, and axial stiffness are given in Table 3.2 when the shape factor is kept constant.

To permit the connection of the model isolators to the reaction blocks, a minimum end plate thickness of 0.75 in. was maintained. The dimensions of the model isolators, for both the concrete and steel buildings are given in Tables 3.3 and 3.4.

Table 3.1

Geometric Similitude Relationship*

Quantity	Relationship
Length, l	$l_M = l_P\ (SF)^{-1}$
Area, A	$A_M = A_P\ (SF)^{-2}$
Mass, m	$m_M = m_P\ (SF)^{-2}$
Weight, W	$W_M = W_P\ (SF)^{-2}$
Time, t	$t_M = t_P\ (SF)^{-0.5}$
Frequency, f	$f_M = f_P\ (SF)^{-0.5}$
Velocity, v	$v_m = v_p\ (SF)^{-0.5}$
Acceleration, a	$a_M = a_P$
Force, F	$F_M = F_P\ (SF)^{-2}$
Stress, σ	$\sigma_M = \sigma_P$
Strain, ε	$\varepsilon_M = \varepsilon_P$
Stiffness, k	$k_M = k_P\ (SF)^{-1}$

* The subscripts M and P represent model and prototype, respectively. SF is an abbreviation for length scale factor (>1).

Table 3.2

Similitude for Key Elastomeric Characteristics

Quantity	Relationship
Stress (σ)	$\sigma_M = \sigma_P$
Strain (ε)	$\varepsilon_M = \varepsilon_P$
Shape Factor (S)	$S_M = S_P$
Buckling Load (P_B)	$(P_B)_M = (P_B)_P\ (SF)^{-2}$
Roll-Out Load (P_{RO})	$(P_{RO})_M = (P_{RO})_P\ (SF)^{-2}$
Stiffness (k)	$k_M = k_P\ (SF)^{-1}$

Table 3.3

Isolator Geometry for Concrete Building

	Full Scale	1/2 Scale	3/8 Scale	1/8 Scale
Rubber: layers, thickness	26, 1/2"	26, 1/4"	26, $^{3}/_{16}$"	26, 1/8"
Steel Shims: layers, thickness	25, 1/8"	25, 16GA	25, 18GA	25, 22GA
Cover Plates: 2, thickness	2, 1 3/4"	2, 7/8"	2, 3/4"	2, 3/4"
Overall Dimensions: Breadth x Width x Height	28" x 28" x 19 5/8"	14" x 14" x 9 3/4"	10 1/2"x 10 1/2" x 7 $^{9}/_{16}$"	7" x 7" x 5 1/2"

Table 3.4

Isolator Geometry for Steel Building

	Full Scale	1/2 Scale	1/4 Scale	Scale
Rubber: layers, thickness	16, 1/2"	16, 1/4"	16, $^{3}/_{16}$"	16, 1/8"
Steel Shims: layers, thickness	15, 1/8"	15, 16GA	15, 18GA	15, 22GA
Cover Plates: 2, thickness	2, 1 3/4"	2, 7/8"	2, 3/4"	2, 3/4"
Overall Dimensions: Breadth x Width x Height	21" x 21" x 13 3/8"	10 1/2 x 10 1/2" x 6 $^{11}/_{16}$"	7/8" x 7/8" x 5 1/4"	5 1/4" x 5 1/4" x 3 $^{15}/_{16}$"

4 USACERL STRUCTURAL TESTING FACILITIES

To develop the most cost-effective tridirectional dynamic testing frame, the capabilities of existing USACERL equipment and facilities were evaluated for incorporation into the design. This chapter presents a description and evaluation of the structural testing facilities and equipment available at USACERL for experimental base isolation studies. This discussion addresses the available testing equipment, its capabilities, and requirements for testing base isolation devices of varying scales. Other options, including modification of the existing actuators and combination of the existing hydraulic pumps to increase the testing capabilities, are also discussed.

USACERL Equipment

Test Load Floor

USACERL facilities for experimental testing of structural systems include a test load floor, located in a high-bay area. The load floor dimensions are 120 ft x 80 ft (36.6 m x 24.4 m) x 2 ft (0.61 m) thick, and it occupies half of the total floor area. It is divided into two parts by a row of columns at a 20 ft (6.10 m) spacing on the long axis centerline of the floor. A 20 ton (44.5 kN) capacity overhead crane is located above the east side of the load floor for moving equipment and structural systems.

The eastern half of the structural test area has receptacles for anchoring test fixtures and equipment to the load floor. The receptacles consist of 2.9 in. (77 mm) inside diameter extra strong steel pipes cast into the load floor. The receptacles are placed on 3 ft (0.91 m) centers covering nearly the entire eastern half of the floor. Each receptacle is rated to resist 60 kips (267 kN) load in any direction.

Hydraulic Actuators

USACERL has five hydraulic actuators for static and dynamic testing of structural components. The load in each actuator is controlled by a closed-loop electro-hydraulic system. The performance specifications of these five actuators are given in Table 4.1.

The maximum dynamic force capacities are 30.4 kips (135 kN) for three of the actuators and 61.8 kips (275 kN) for the remaining two actuators. The maximum stroke length of all five actuators is 6 in. (152 mm), that is, ±3 in. (±76 mm).

Each actuator is equipped with a servo-valve unit which regulates the direction and rate of flow of the hydraulic fluid to the hydraulic actuator. The servo-valves function as the final control element in a closed-loop system. The maximum flow capacity of the existing servo-valves is 40 gpm (151 liters/min). The maximum flow is associated with approximately a 1000 psi (6900 kPa) pressure drop in the servo-valves.

The hydraulic actuators needed to test base isolation devices must have a large force capacity, stroke length, and servo-valve flow rate. Due to the limited capacities of the existing actuators, the possibility of modifying some of the actuators to increase their stroke length was investigated. The maximum force and stroke length of a hydraulic actuator at a given velocity is limited by either the physical dimensions of the actuator rod and cylinder, or by the flow capacity of the servo-valve. In the latter case, it is feasible to replace the servo-valve with one which can provide a higher flow capacity to achieve greater displacements (strokes). Because the actuators at USACERL (Table 4.1) are limited by their physical geometry, replacing the servo-valves would not increase their stroke or force capacity, but would increase the maximum speed of the test. The requirements for, and ramifications of, replacing the servo-valves should be evaluated by USACERL in conjunction with actuator manufacturers.

Table 4.1

USACERL Hydraulic Actuators Performance Specifications

	Units	Actuator Numbers				
		1	2	3	4	5
Model *		307-25-40-6-LV-SB	307-25-40-6-LV-SB	307-25-40-6-LV SB	307-50-40-6 LV-SB	307-50-40-6-LV-SB
Serial No.		3186	3187	3188	3189	3190
Stall Force	kips (kN)	30.4 (135)	30.4 (135)	30.4 (135)	61.8 (275)	61.8 (275)
Dynamic Force	kips (kN)	25 (111)	25 (111)	25 (111)	50 (222)	50 (222)
Servo-valve flow @ 1000 psi (6,890 kPa)	gpm (lpm)	40 (151)	40 (151)	40 (151)	40 (151)	40 (151)
Rated Velocity	in/sec (mm/sec)	22 (559)	22 (559)	22 (559)	11 (279)	11 (279)
Stroke	in (mm)	6 (152)	6 (152)	6 (152)	6 (152)	6 (152)

*LV = AC displacement transducer; SB = swivel base; gpm = gallons per minute; lpm = liters per mintute.

Hydraulic Pumps

The fluid in the actuators is pressurized by hydraulic pumps and transferred through high pressure lines to the servo-control valves. Currently the USACERL structural testing facilities have several hydraulic pumps each having different flow capacities. Table 4.2 shows the flow capacities and the associated power ratings of these pumps.

Due to the projected demands for testing the base isolation devices, the output of several pumps may have to be combined. Using a multipump system with a larger flow capacity was considered for design of the proposed test program and is discussed in the following sections. It is common practice to connect hydraulic pumps in parallel to efficiently use their combined capacities. The manufacturers of hydraulic pump systems should be consulted to determine the required hardware and control systems.

To take advantage of the capacity of the pumps in the USACERL biaxial shock test machine (BSTM), a high-pressure line could be installed between the two buildings, and a system for combining output from the three pumps could be constructed.

Power Supply

The USACERL structural testing facilities do not use in-house power generators. The power required for operating the structural testing equipment is supplied by external sources. The power demand and costs for the base isolation experiments must be assessed by USACERL staff.

USACERL Load Frame

USACERL structural testing facilities include a 1000 kip (4450 kN) load frame. This frame can apply static and dynamic axial compression and tension loads.

Table 4.2

USACERL Hydraulic Capacities*

	Total Flow Capacity gpm (lpm)	Total Power Demand HP (kW)
STRUCTURAL TESTING LAB		
1 CGS pump with 1 super charge pump	120 (454)	260 (196)
1 MTS pump with 1 super charge pump	70 (265)	133 (99)
BSTM FACILITY		
4 pumps plus 2 super charge pump	280 (1060)	515 (384)

* Rated at standard pressure of 3000 psi (20.7 MPa).

Instrumentation and Data Acquisition System

The data acquisition system available for recording test data on the load floor can accommodate up to 100 channels of information with the use of high speed electronic recording equipment, analog-to-digital (A-D) conversion units, and one 79 channel magnetic tape recorder.

Limitations on the Proposed Testing Program

Base isolation devices are designed to carry the gravity load of the structural column or tributary wall, or structure above the device. During severe earthquake shaking, the isolators will undergo substantial lateral deformation. To simulate their seismic behavior, the test loading mechanism must apply forces and displacements on the test specimen which are comparable to those expected in an actual isolator. This condition imposes enormous demands on the capacity of the actuators, hydraulic system, and power generators which drive the actuators, and the reaction frame. To reduce these demands to meet the available capacities of the USACERL structural testing facilities and to maintain a realistic simulation of isolator properties, the maximum scale of the concrete building isolator is half-scale. At this scale, the elastomeric isolators can be subjected to compressive stresses of more than 1000 psi and shear strains exceeding 200 percent at reasonable loading frequencies. The limits of 1000 psi and 200 percent shear strain were chosen because (1) 1000 psi is the maximum compressive stress under dead load plus live load as permitted by the American Association of State Highway and Transportation Officers (AASHTO), and (2) 200 percent shear strain is a reasonable limit on shear strain in elastomeric isolators.

In addition to using smaller specimens, the limitations of the available hydraulic pumps and power generators were also considered in design of the hardware and the test program.

Actuator Layout

For testing base isolator devices subjected to one-dimensional horizontal displacement, three actuators are required:

- One horizontal actuator applies lateral loads (displacement)
- Two vertical actuators apply axial compressive stress and restrain rotation at the top of specimen.

For two-directional horizontal testing, six actuators are required:

- Two horizontal actuators apply lateral loads (displacements) in two perpendicular directions
- One horizontal actuator restrains the specimen from twisting about a vertical axis
- One vertical actuator applies axial compression
- Two vertical actuators restrain rotation at the top of specimen.

The locations and mountings of the different actuators in the test frame are discussed in Chapter 5.

Actuator Capacity Demands

The maximum shear strength of the half-scale isolation device is expected to be about 90 kips (400 kN). For high damping rubber bearings or lead-rubber bearings, the scaled specimens are expected to deform laterally approximately 16 in. (41 cm) to reach 200 percent shear strain. Table 4.3 summarizes the actuator force and stroke length demands during the bidirectional horizontal testing of a single elastomeric bearing to a deformation level of 200 percent shear strain. The testing system (actuators, servo-control valves, required hydraulic pumps, and power generator) must have sufficient capacity to impose forces and displacements at a realistic frequency on the specimen.

Required Fluid Flow Capacity

The required fluid flow rate to drive the hydraulic actuators may be estimated by the following equation:

$$\text{Flow Demand} = (\text{Stroke})\ (\text{Actuator Area})\ (\text{Frequency}) \qquad [\text{Eq } 4]$$

This equation is based on a root mean square (RMS) average of sinusoidal cyclic motion. For example, to drive a 90 kip (400 kN) actuator with an effective piston area of 38.48 in^2 (248.28 cm^2), and a stroke length of ±16 in. (±41 cm), at a frequency of 0.50 Hz, the fluid flow demand (D_f) is:

$$\begin{aligned} D_f &= (2 \times 16 \text{ in.})\ (38.48 \text{ in}^2)\ (0.50 \text{ Hz})\ (60 \text{ sec/min})\ (0.00433 \text{ gal/in}^3) \qquad [\text{Eq } 5] \\ &= 160 \text{ gpm } (605 \text{ lpm}) \end{aligned}$$

Options for Combining Pump Output of Existing Actuators

Because the fluid flow rate directly affects the maximum specimen displacement and test speed, the possibility of combining the output of several hydraulic pumps to increase the flow rate was considered during the development of the test program. Figure 4.1 shows the estimated required flow rate during 1-D and 2-D tests at 32 in. (81 cm) specimen displacement, as a function of testing period (period = 1/frequency). Figures 4.2 through 4.4 show three limiting flow capacities of the existing pumps.

Option 1

Using only the 120 gpm (454 lpm) pump, specimens can be cycled at relatively long periods of approximately 4 seconds and 9 seconds during 1-D and 2-D tests, respectively, to a lateral displacement of ±16 in. (±41 cm), that is a stroke length of 32 in. (81 cm). The associated test speeds are, 8 in./sec (20 cm/sec) and 3.6 in./sec (10 cm/sec), respectively. When specimens are tested at a higher frequency, the lateral displacement amplitude must be reduced. Figure 4.2 shows the estimated maximum attainable specimen displacements as a function of testing period.

Table 4.3

Actuator Force and Stroke Length

Actuator	Orientation	Expected Demand	
		Force (kips/kN)	Stroke Length (in./cm)
1	Horizontal	±90/400	±18/±46
2	Horizontal	±90/400	±18/±46
3	Horizontal	±35/160	±18/±46
4	Vertical	±220/890	±3/±8
5	Vertical	±50/220	±3/±8
6	Vertical	±50/220	±3/±8

Option 2

When the 120 gpm and 70 gpm pumps are combined, a flow rate of approximately 190 gpm (720 lpm) can be obtained. At this rate, specimens can be cycled at approximately 3 second and 5 second periods for the 1-D and 2-D tests, respectively, to a lateral displacement of ±16 in. (±41 cm). The associated test speeds are 10.5 in./sec (27 cm/sec) and 6.4 in./sec (16 cm/sec), respectively. Figure 4.3 shows the estimated maximum attainable specimen displacements as a function of testing period, for this rate of fluid flow. It is estimated that the power consumption during the simultaneous operation of these pumps is approximately equal to that consumed during an earthquake simulator test.

Option 3

When the additional capacity of the 280 gpm (1060 lpm) pumps in the BSTM facility are included, the specimens can be tested at periods of 1.2 seconds and 2 seconds for the 1-D and 2-D tests, respectively, to a lateral displacement of ±16 in. (±41 cm). Figure 4.4 shows the estimated maximum specimen displacements at this flow rate, as a function of testing period.

Evaluation of the Options

The testing frequency and displacement that can be achieved using Option 1 would not be adequate for testing large scale isolators at or near realistic frequencies and lateral displacements. Thus, the effect of frequency dependence on isolator behavior could not be studied. Option 2, on the other hand, provides a cost-effective increase in testing capability and would be acceptable for the USACERL base isolation study. The additional expenses of Option 3, which include installing high pressure lines from the BSTM facility and the costs associated with operating all pumps simultaneously, may not be justified by the relative increase in testing speed.

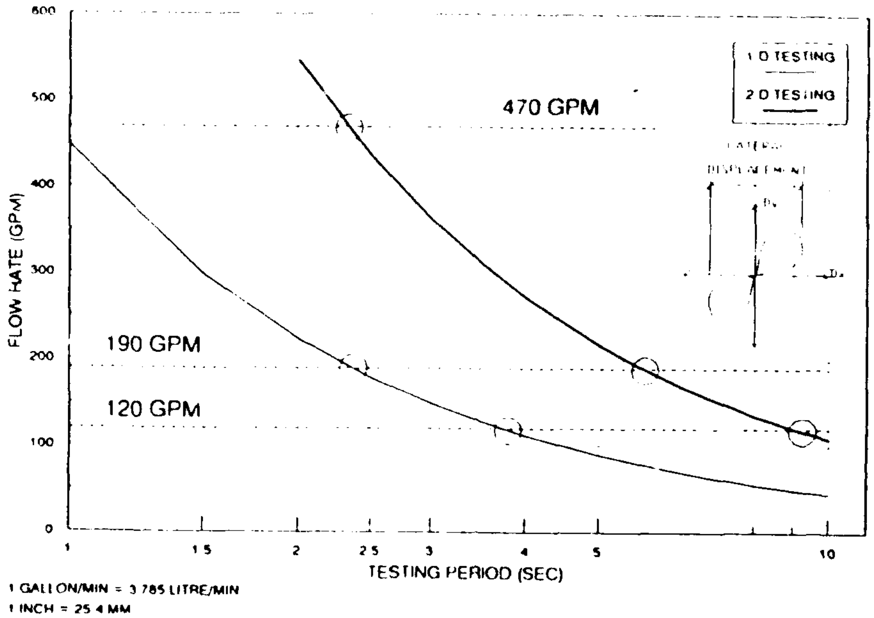

Figure 4.1. Flow Rate vs Testing Period Relationship at Lateral Displacement of 32 in.

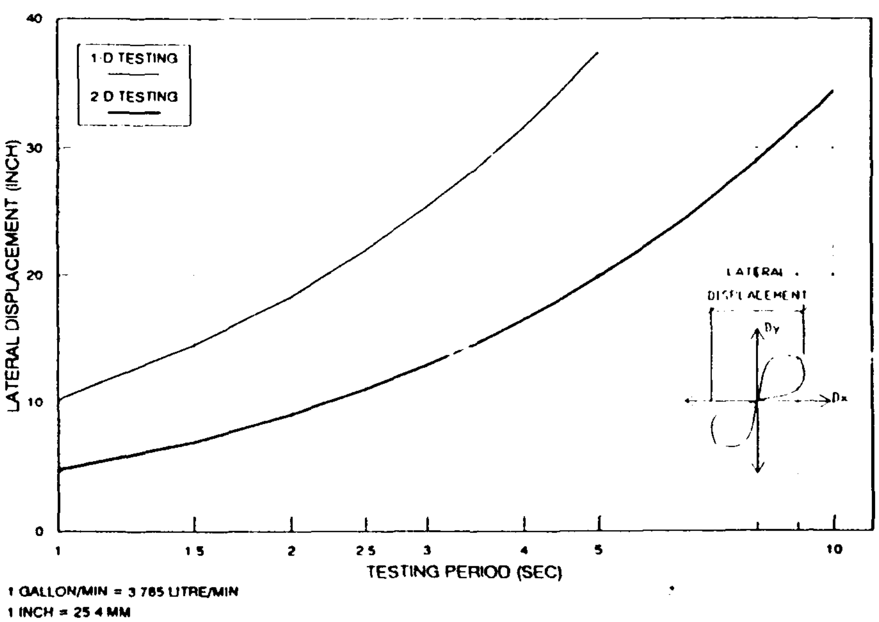

Figure 4.2. Lateral Displacement Capacity With 120 gpm Pump.

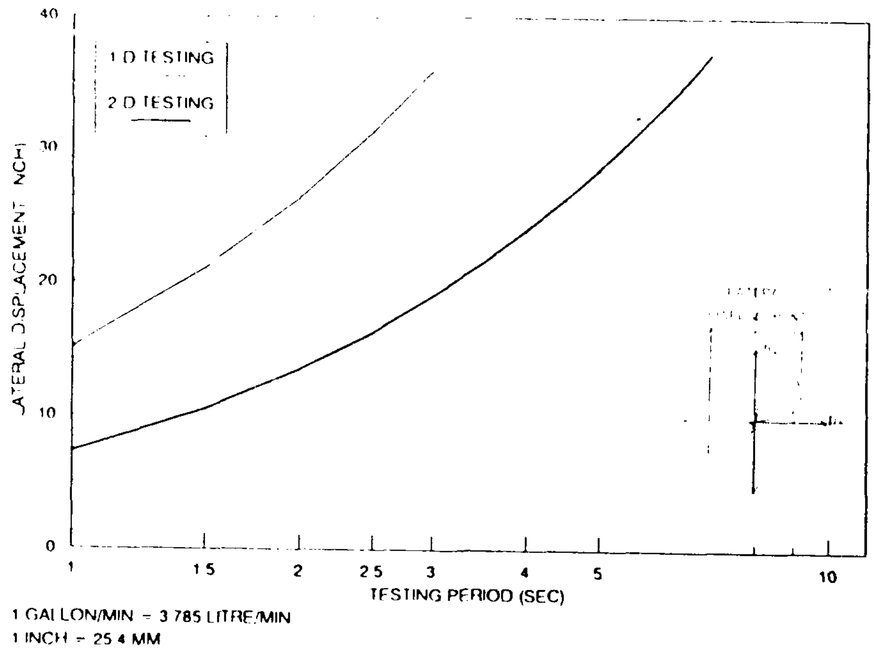

Figure 4.3. Lateral Displacement Capacity With 120 gpm Pump.

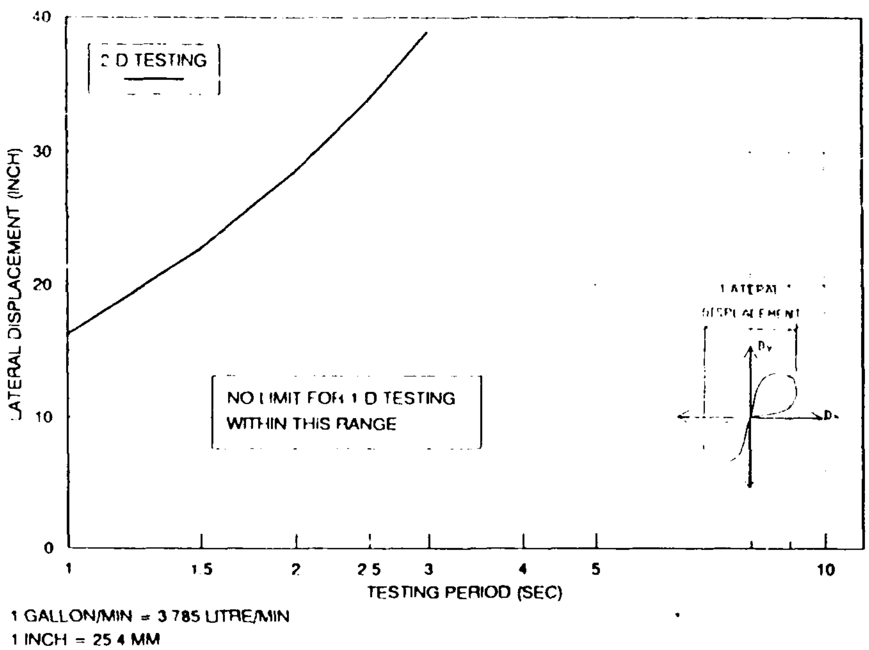

Figure 4.4. Lateral Displacement Capacity With 470 gpm Pump.

5 DESIGN FOR TRIDIRECTIONAL REACTION FRAME

A three-dimensional steel frame has been designed for testing base isolation devices under various tridirectional combinations of axial and lateral force and displacement. The frame is intended to be installed and anchored to the load floor in the USACERL structural testing facility. The reaction frame provides the support for the test specimen, loading mechanism (consisting of six servo-controlled hydraulic actuators and accessories), and data acquisition transducers. This chapter presents the design criteria and a description of the reaction frame and of the equipment mountings.

Alternative Design Concepts

Several test setups were considered for the design of the reaction frame for the tridirectional isolator tests. The alternative designs are divided into three groups. Figure 5.1 shows schematic diagrams of these basic designs. The advantages and disadvantages of the basic designs are discussed below.

Design A

This is a single specimen test setup with a moveable top reaction block. Advantages include the following:

- The force capacity requirement of horizontal actuators is relatively low
- Rotation at the top of the specimen is restrained by a multiple vertical actuator system
- The lateral loads and moments on the actuators are minimized.

The disadvantages of this design include the following:

- The control system to maintain the top reaction block level during lateral displacement is complicated
- Six actuators with spherical swivel connectors are required.

Design B

This is a single specimen test setup with sliding bottom reaction block. Advantages include the following:

- Control system to maintain a level top reaction block is simple
- Vertical actuators do not require swivel connectors.

The disadvantages of this design are the following:

- Construction of a frictionless sliding surface is extremely difficult and expensive
- The specimen shear resistance cannot be directly measured without designing and installing a large capacity load cell.

Design C

This is a double specimen test setup with moveable middle reaction block. Advantages include the following:

- Swivel connectors are not required for the vertical actuators
- Control system to maintain a level top reaction block is simple.

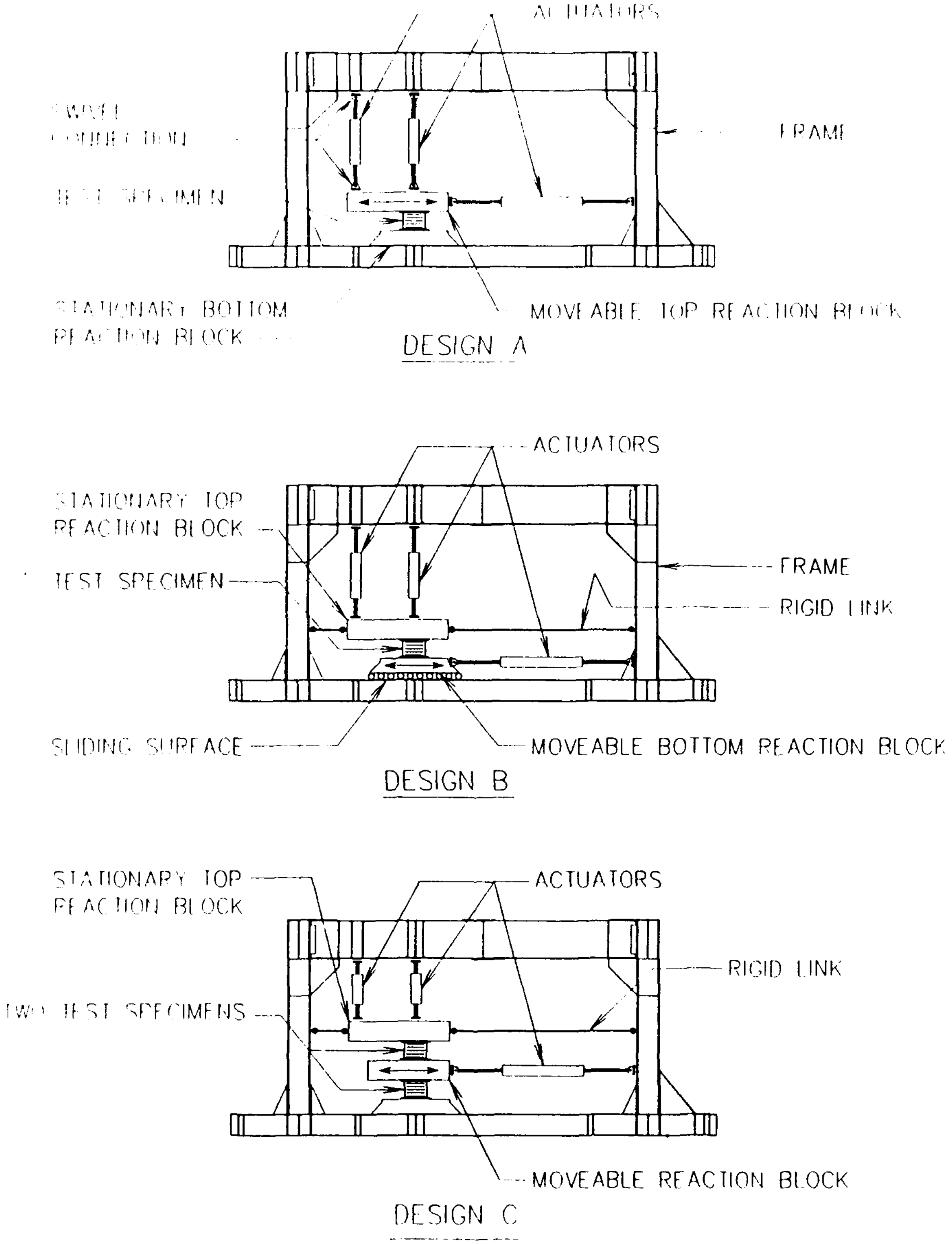

Figure 5.1. Alternative Design Concepts for Reaction Frame.

The disadvantages of this design are that:

- The horizontal actuator force demand is doubled
- The increased height of the specimen will require higher frame clearance
- The frame is larger and heavier than those needed for Designs A and B.

Due to the limitations of the available hydraulic pump system and the required precision of the testing program, Design A was selected as most appropriate for the USACERL base isolation study.

Frame Dimensions

The maximum frame dimensions are approximately 25 ft x 25 ft (7.62 m x 7.62 m) at the base of the frame and 19 ft x 19 ft (5.79 m x 5.79 m) at the top of the frame. The total height of the frame above the test floor is 11 ft, 2 in. (3.40 m). The estimated weights of the frame's components and total frame weight are given in Table 5.1.

Design Criteria

The reaction frame was designed to support the test specimen and the actuators, be sufficiently rigid to minimize distortion of the frame members, and facilitate displacement measurement and actuator control during the cyclic tridirectional tests. The maximum actuator forces listed in Table 4.3 were used for the design of the reaction frame. The forces were applied where the actuators connect to the frame. The direction along which the actuator reaction is applied to the frame depends on the relative position of the ends of the actuators and the deformed shape of the test specimen. Because the base isolation devices will be subjected to large lateral displacements, the frame stability and displacement were examined under various combinations of horizontal and vertical forces all applied in different directions. The maximum frame displacements occur at the connection points to the actuators. Under the most severe loading condition, the maximum displacement in the frame, at its connection to the 200 kip vertical actuator, is approximately 0.16 in. (4 mm). Figure 5.2 shows the calculated deformed state of the reaction frame. The deflections in this figure are exaggerated.

The reaction frame will be subjected to cyclic loading by the actuators during testing. Therefore, natural vibration periods were selected such that the loading frequency of the specimen testing will not induce a resonant condition in the frame. A dynamic analysis of the frame was performed to estimate

Table 5.1

Reaction Frame Weights

Component	Weight (lb/kN)
Top Framing	3,600 / 16
Base Framing	8,200 / 37
Columns and Braces	5,200 / 24
Top Reaction Block	1,200 / 6
Bottom Reaction Block	2,600 / 12
Total	20,800 / 95

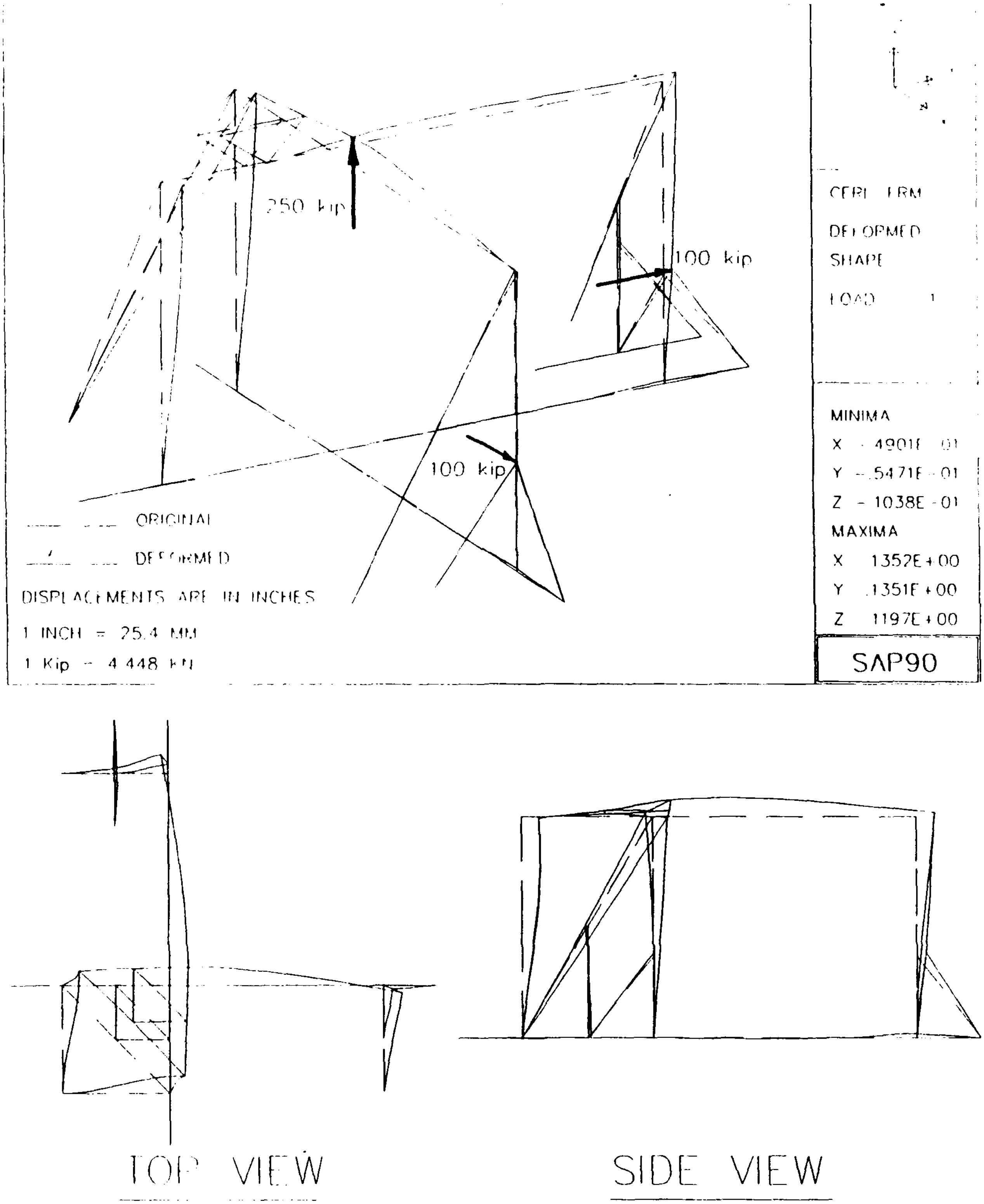

Figure 5.2. Deflected Shape of Test Frame.

natural vibration periods and mode shapes of the frame. The reactive masses used in the analysis included the weight of frame members plus the additional weight of the attached loading mechanism. The calculated vibration period of the first mode was 0.036 sec, that is, a frequency of 28 Hz.

The reaction frame will be anchored to the test load floor receptacles to increase its rigidity and its lateral strength. The frame base dimensions were selected to align with the loading floor receptacles.

The required clearance for installation of the actuators was a major factor in designing the reaction frame geometry. The proposed frame layout allows 9 ft, 10 in. (300 cm) and 5 ft, 10 in. (178 cm) of clearance for installation of the horizontal and vertical actuators, respectively. These clearances include dimensions of the actuator, head and base swivels, load cells, and accessories.

Description of Reaction Frame

The structural drawings and details of the reaction frame are presented in Appendix A. The frame is composed of two perpendicular steel frames which support the actuators and the test specimen. The frame members are laterally braced at their connections and where the actuator reactions are imparted to the frame. Bolted connections are used so the frame could be dismantled, stored, and relocated.

Base Framing

The base framing of the reaction frame is composed of 14 in. (35.6 cm) deep steel W sections and bolted connections. A layer of steel grating is installed on the W sections to provide a working surface.

Columns and Braces

The frame columns are composed of 14 in. (35.6 cm) deep steel W sections. The columns have moment resisting connections to the base and top framing beams. Steel double angle sections and plates at the frame joints give lateral stability to the columns and where the actuator reactions are imparted to the columns. Stiffener plates are used to strengthen the column webs at the load application points.

Top Framing

The top framing beams are composed of 24 in. (61 cm) deep steel W sections. Part of the framing, which consists of a beam-to-beam connection and lateral bracing of the actuator support points, is built as a single unit with welded connections. The individual parts of the top framing and column connections will be assembled in the structural test laboratory with high strength friction-grip bolts.

Reaction Blocks

To secure the test specimen to the base framing beams and to apply loads at the top of the specimen, two reaction blocks are used. Each reaction block consists of a 2 in. (51 mm) steel plate stiffened with steel plates and WT sections.

Specimen Mounting

The base isolation devices will have top and bottom steel plates attached to them for installation in the test frame. The type of attachments (and bolt hole locations for the bolted isolators) will vary from specimen to specimen.

For securing the test specimen to the reaction blocks, a special steel plate must be machined for each specimen. These plates will have holes drilled at standard locations to match the reaction block bolt holes and holes for attachment to the specimen.

Actuator Mountings

Actuators 1 and 2 (Figure 5.3) are the main horizontal actuators which impose the required lateral displacements on the specimen in the two perpendicular directions. Actuator 3 is required to prevent twisting of the top reaction block (and the test specimen) during bidirectional lateral displacement. The swivel ends of horizontal actuators are connected by bolted steel plates to the supporting columns and top reaction block.

The axial compressive load on the test specimen is applied by Actuator 4. Actuators 5 and 6 are needed to keep the top reaction block level and prevent rotation at the top of the specimen during the lateral displacement of the specimen. The swivel ends of the vertical actuators are connected to the bottom flanges of the frame beams and to the top reaction block by high strength bolts.

The swivel end connectors allow the actuators to follow the movement of the top reaction block during testing and to minimize lateral loads on the actuator shaft. Swivel joints may rotate in two directions. Each horizontally mounted actuator may rotate ±10 degrees in the horizontal plane. In the vertical direction, the actuators must be able to rotate ±5 degrees to account for different size specimens, and the axial shortening of the specimens during testing. The vertical actuators' swivel ends may rotate about ±23 degrees in two directions to follow the lateral displacement of the top reaction block. The minimum required rotation angles of the swivel connectors are listed in Table 5.2.

Instrumentation

A list of the load cells and transducers required for the testing program is presented in Table 5.3. The data obtained from the instrumentation for these tests will allow development of tridirectional force-deformation relationships for the individual bearings and provide some redundancy in the data acquisition process.

The axial force and displacements in the actuators are measured by load cells and linear variable differential transducers (LVDTs) built integrally with the actuators. During cyclic testing of the isolators, the acceleration of the movable top reaction block and other attached masses will affect the forces on the test specimens. The components of the reaction block acceleration will be measured by three accelerometers.

The displacement of the test specimen can be completely defined by the relative location of the top reaction block and the fixed base of the test frame. To measure the displacements of the reaction block, 13 direct current differential transducers (DCDTs) will be used; four mounted vertically between the top and base reaction blocks, and eight installed diagonally to measure the relative lateral displacement and rotation of the top and base reaction blocks. Lateral displacement and twisting of the top of the test specimen is measured by an LVDT/DCDT installed horizontally between the top reaction block and the test frame (see Figure 5.2).

Equipment Purchases

The proposed test program was developed with the objective of using as much of the existing equipment at USACERL as possible. However, due to the high force and displacement demands of the testing program, actuators with significantly larger force and displacement capacities must be purchased

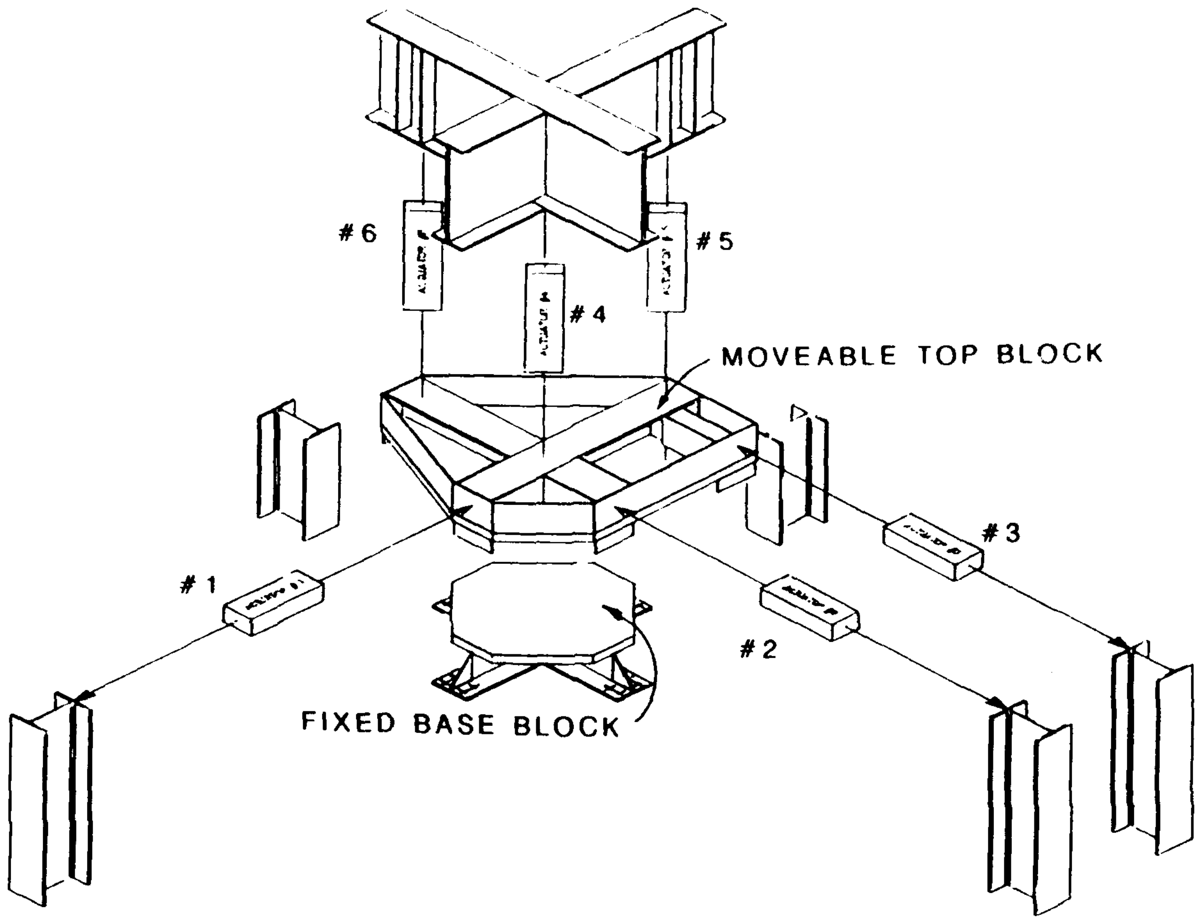

Figure 5.3. Actuator Locations.

(Table 5.4). For Actuators 5 and 6, the existing USACERL actuators rated for 50 kips (222 kN) may be used. However, new swivel head and base connectors must be purchased for these actuators.

The testing setup and actuators are selected to function with the existing hydraulic pumps in the USACERL structural testing laboratory. However, the requirements for combining the output of the 120 gpm and 70 gpm pumps should be assessed and appropriate hardware purchased.

Table 5.2

Required Angle of Head and Base Swivel

Actuator	Swivel Rotation
1, 2, and 3	± 5° Vertical Plane ± 10° Horizontal Plane
4, 5, and 6	± 23° Each Direction

Table 5.3

Load and Displacement Measurement Instruments

Item	Measurement	Quantity
Load Cells	Actuator Force	6
LVDT *	Actuator Displacement	6
LVDT/DCDT**	Displacement of the Top Reaction Blocks	13
Accelerometer	Acceleration of the Top Reaction Blocks	3
Total Number of Data Channels		28

*LVDT: linear variable displacement transducer.
**DCDT: direct current displacement transducer.

The availability of the required DCDTs and LVDTs, accelerometers, and data acquisition equipment in the current USACERL inventory should be investigated by USACERL staff. New transducers should be purchased as necessary.

Cost Estimates

To assist the USACERL in assessing and planning the proposed tridirectional test program, an estimate of the main equipment upgrade costs was obtained. The estimate includes the cost of the reaction frame, four actuators with their attachments, and accessories as follows:

Reaction Frame	$40,000
Actuators 1 & 2	$80,000 each
Actuator 3	$40,000
Actuator 4	$80,000
Hydraulic Service Manifolds	$35,000
Actuator Accessories	$30,000

These estimates are based on the unit weight cost of steel frames and typical actuator specifications. A contingency of 20 percent should be added to these figures. The cost of evaluating the hydraulic pump system and the required hardware to combine these pumps was not included. Pump suppliers should be consulted for these costs. Another cost item which is not included in this estimate is that associated with the design and implementation of a control procedure for tridirectional testing. The required work and associated costs of this item should be determined by USACERL technical staff in consultation with actuator suppliers.

Table 5.4

Specifications for New Actuators

Item	Rating	Comments
Actuators 1 and 2 each with load cell, servo-valve and swivel connector	±100 kips (445 kN) force; ±18 in. (±46 cm) stroke; 150 gpm (757 lpm) flow; ±5° Vertical Swivel, ±10° Horizontal Swivel	Total length of the assembly should not exceed 9'-1" (300 cm)
Actuator 3 with a load cell, servo-valve and swivel connector	±35 kips (156 kN) force; ±18 in. (±46 cm) stroke; 30 gpm (114 lpm) flow; ±5° Vertical Swivel, ±10° Horizontal Swivel.	Same as Actuators 1 and 2.
Actuator 4 with a load cell, servo-valve and swivel connector	±220 kips (980 kN) force; ±3 in. (±8 cm) stroke; 65 gpm (250 lpm) flow; ±23° swivel, two directions.	Total length of the assembly should not exceed 5'-10" (178 cm).

6 DESCRIPTION OF THE PROPOSED TESTING PROGRAM

Design Parameters

The dynamic response of a base-isolated building can be influenced by a number of factors. These factors differ for elastomeric and sliding isolation systems. For elastomeric isolation systems, important design or response parameters include:

- Axial stress and strain
- Shear stress and strain
- Equivalent viscous damping (horizontal and vertical)
- Loading frequency
- Stability (buckling, rollout)
- Low-cycle fatigue.

For sliding isolation systems, important design and response parameters include:

- Contact pressure
- Sliding velocity
- Static and dynamic coefficients of friction.

The comparative testing program will investigate each of these parameters and their interdependence, for both the elastomeric and sliding isolation systems.

Testing To Be Performed in the Reaction Frame

The proposed tridirectional testing frame will be used for most of the parametric and comparative studies listed above for both elastomeric and sliding isolation systems.

Elastomeric Isolators

The interdependence of axial stress (σ_a) and axial strain (ε_a), shear stress (τ) and shear strain (γ), equivalent viscous damping (ξ), frequency (f) and bearing stability (rollout, buckling) for each isolation system will be investigated as indicated in Table 6.1. Comparative test data will be collected and reduced for benchmark displacements and axial forces. The appropriate benchmarks will be selected after consultation with the vendors and the other participants in the research program.

Sliding Isolators

The interdependence of contact pressure (p_c), sliding velocity ($\dot{\upsilon}$) and the static (cof_s) and dynamic (cof_d) coefficients of friction will be investigated as indicated in Table 6.2. Comparative test data will be collected and reduced for benchmark displacements and axial forces. The appropriate benchmarks will be selected after consultation with the vendors and the other participants in the research program.

Testing To Be Performed on the Load Frame

The load frame at USACERL will be used to evaluate:

- The axial stiffness of the elastomeric isolators
- The tensile strength of the elastomeric isolators

Table 6.1

Design Parameter Interdependence of Elastomeric Isolators

Parameter	σ_a, ε_a	τ, γ	ξ	f	Stability
σ_a, ε_a		✓	✓		✓
τ, γ	✓		✓		✓
ξ	✓	✓		✓	
f			✓		
Stability	✓	✓			

Note: ✓ denotes probable interdependence

- The vertical damping characteristics of the elastomeric isolators (at zero percent shear strain) at large axial strains.

The 500 ton load frame will permit these parameters to be evaluated at higher levels of axial force than could otherwise be attained in the proposed tridirectional reaction frame.

Participants in the Research Program

All known base isolation vendors and three reknowned base isolation researchers were contacted and asked if they wanted to contribute to the comparative base isolation testing program. The individuals and companies contacted are listed in Appendix B. Of the eight vendors contacted, five have replied

Table 6.2

Design Parameters Interdependence of Sliding Isolators

Parameter	p_c	$\dot{v}$	cof_s	cof_d
p_c		✓	✓	✓
$\dot{v}$	✓			✓
cof_s	✓			
cof_d	✓	✓		

Note: ✓ denotes probable interdependence.

indicating a willingness to participate in the research program and to supply isolators at no charge to the Government for the comparative testing program. The extent of interest shown by these eight companies and individuals is tabulated in Table 6.3.

Table 6.3

Participants in the Research Program

Company/ University	Individual	Academic Interest	Isolator Supply	
			Elastomeric	Sliding
BRIDGESTONE	R.A. Busch		✓	
D.I.S.	R.L. Mayes		✓	
E.P.S.	V.A. Zayas			✓
FREYSSINET	JPh. Fuzier		✓	✓
FYFE	E. Fyfe		✓	
ISOSYS	G. Delfosse	✓		
PCR	P.C. Rizzo	✓		
SUNY	I.G. Buckle	✓		
SUNY	M.C. Constantinou	✓		
UCB	J.M. Kelly	✓		

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

Static and dynamic testing of base isolation systems has been conducted in the United States, New Zealand, and Japan for more than a decade. However, because most of the testing has been vendor-sponsored, there are no comparative test data available for engineers to use in judging the effectiveness and applicability of the different isolation systems for a specific project.

The major objectives of the proposed research program are to (1) develop a database of testing results for comparing the response of different isolation systems, (2) undertake analytical studies of the behavior of different isolation systems using constitutive models developed in Phase 1 and, (3) prepare specifications, guidelines, and construction details to aid the engineering profession with implementation of base isolation systems.

Phase 1 of the research program includes (1) the design, documentation, and construction of a reaction frame for three-dimensional dynamic testing of third-to-half-scale isolation units, (2) development and performance of a detailed testing program that will investigate isolator behavior under different loading environments, and (3) reduction of the data acquired during the testing program and preparation of a detailed technical report that will include an extensive discussion on comparative isolator responses. This report presents the design and documentation of the reaction frame and discusses development of the detailed testing program.

To ensure that the test results will be useful to the engineering profession, every effort was made to design realistic full-scale prototype isolators. A five-story concrete building and a three-story steel building were chosen for analysis purposes. The design of the full-size scale isolators for these two buildings assumes the use of high-damping rubber bearings manufactured using a 246-70 compound. The components in the typical full-scale isolators are listed in Table 7.1.

The parameters of stress, strain, and shape factor were kept constant for the design of the model isolators. To connect the model isolators to the reaction blocks in the testing frame, a minimum end plate thickness of 3/4 in. was maintained. The dimensions of the model isolators, for both the concrete and steel buildings at full-, half-, three-eighths-, and quarter-scales, are given in Table 7.2.

For one-dimensional horizontal testing of isolation devices, three servo-actuators are required; for two-dimensional horizontal testing, six actuators are required. USACERL has five hydraulic actuators for static and dynamic testing. However, because their force capacities are low (3 x 25 kips, 2 x 50 kips) and they have only ±3 in. of stroke, they cannot be used as primary horizontal or vertical actuators.

Table 7.1

Full-Scale Isolator Components

Concrete Building	Steel Building
28" x 28" x 19 5/8" (high)	21" x 21" x 13 3/8" (high)
26, 1/2" thick rubber layers	16, 1/2" thick rubber layers
25, 1/8" thick steel shims	15, 1/8" thick steel shims
2, 1 3/4" thick steel end plates	2, 1 3/4" thick steel end plate

Table 7.2

Model Isolator Dimensions

	Concrete Building			Steel Building		
Scale	Breadth	Width	Height	Breadth	Width	Height
Full	28"	28"	19 5/8"	21"	21"	13 3/8"
1/2	14"	14"	9 3/4"	10 1/2"	10 1/2"	6 14"
3/8	10 1/2"	10 1/2"	7 9/16"	7 7/8"	7 7/8"	5 1/4"
1/4	7"	7"	5 1/2"	5 1/4"	5 1/4"	3 15/16"

Three options were considered to meet the projected hydraulic flow demands for the testing of the base isolation devices. The options included (1) using the standard 120 gpm pump alone, (2) combining the 120 gpm and 70 gpm pumps to provide 190 gpm capacity, and (3) developing a multipump system that combined the 190 gpm capacity in the high bay and the 280 gpm pumps in the BSTM laboratory. The influence of pump capacity on specimen displacement and loading frequency is discussed in Chapter 4. Options 1 and 2 are economically feasible; option 3 is expensive and would require the construction of a concrete trench between the BSTM facility and the high bay, and the provision of new high pressure hydraulic lines.

To test the isolation specimens to 200+ percent shear strain (elastomeric isolators), at a reasonable rate of loading (frequency), with a realistic level of axial load, a maximum isolator scale of one-half was selected. Using the one-half scale concrete building isolator and lateral displacement(s) equivalent to 100 percent and 200 percent shear strain, the loading frequencies noted in Table 7.3 can be attained with the 120 gpm and 190 gpm pump options.

Several alternative reaction frame designs were developed. Each had advantages and disadvantages. The most cost-effective design involved the testing of single isolator specimens which minimized the required capacity of the horizontal actuators (and the hydraulic system). The reaction frame was designed to support the test specimens, and to resist the imposed actuator forces with sufficient stiffness and strength. The actuator forces used for the design were the maximum forces that could be imparted by the actuators to test the one-half scale concrete building isolators at 200 percent shear strain.

Table 7.3

USACERL Testing Options*

Testing	Shear Strain	120 gpm Capacity	190 gpm Capacity
Uni-directional	100%	0.60 Hz	1.0 Hz
Uni-directional	200%	0.75 Hz	0.40 Hz
Bidirectional	100%	0.25 Hz	0.40 Hz
Bidirectional	200%	0.11 Hz	0.16 Hz

*Note that a loading frequency of 0.40 Hz corresponds to an isolated period of 2.5 seconds.

The dynamic response of a base isolated building can be influenced by a number of factors that differ for elastomeric and sliding isolation systems; these parameters are listed in Chapter 6. The comparative testing program will investigate each of these parameters and their interdependence on one another. The testing program will make use of both the proposed tridirectional testing frame and the existing load frame. Comparative test data will be collected and reduced for benchmark displacements and axial forces. The appropriate benchmarks will be selected after consultation with all of the vendors contributing to the project and with the other project participants.

Recommendations

To complete Phase 1 of this multiphase research program, it is recommended that USACERL:

- Construct the reaction frame documented in Appendix A
- Purchase four servo-controlled hydraulic actuators (and the required swivel connectors) with the characteristics listed in Table 7.4
- Purchase sufficient transducers and conditioners to complete the instrumentation requirements presented in Chapter 5.

Table 7.4

Characteristics of Recommended Actuators

Actuator No.	Force Capacity (kips)	Stroke (in.)	Servo-Valve Capacity (gpm)
1	± 100	± 18	150
2	± 100	± 18	150
3	± 35	± 18	30
4	± 220	± 3	65

METRIC CONVERSION TABLE

1 ft = 0.3048 m
1 gpm = 0.063 l/sec
1 in. = 2.54 cm
1 kip = 453.6 kg
1 psf = 4.882 kh/m^2
1 psi = 703.1 kg/m^2
1 ton = 907.1848 kg

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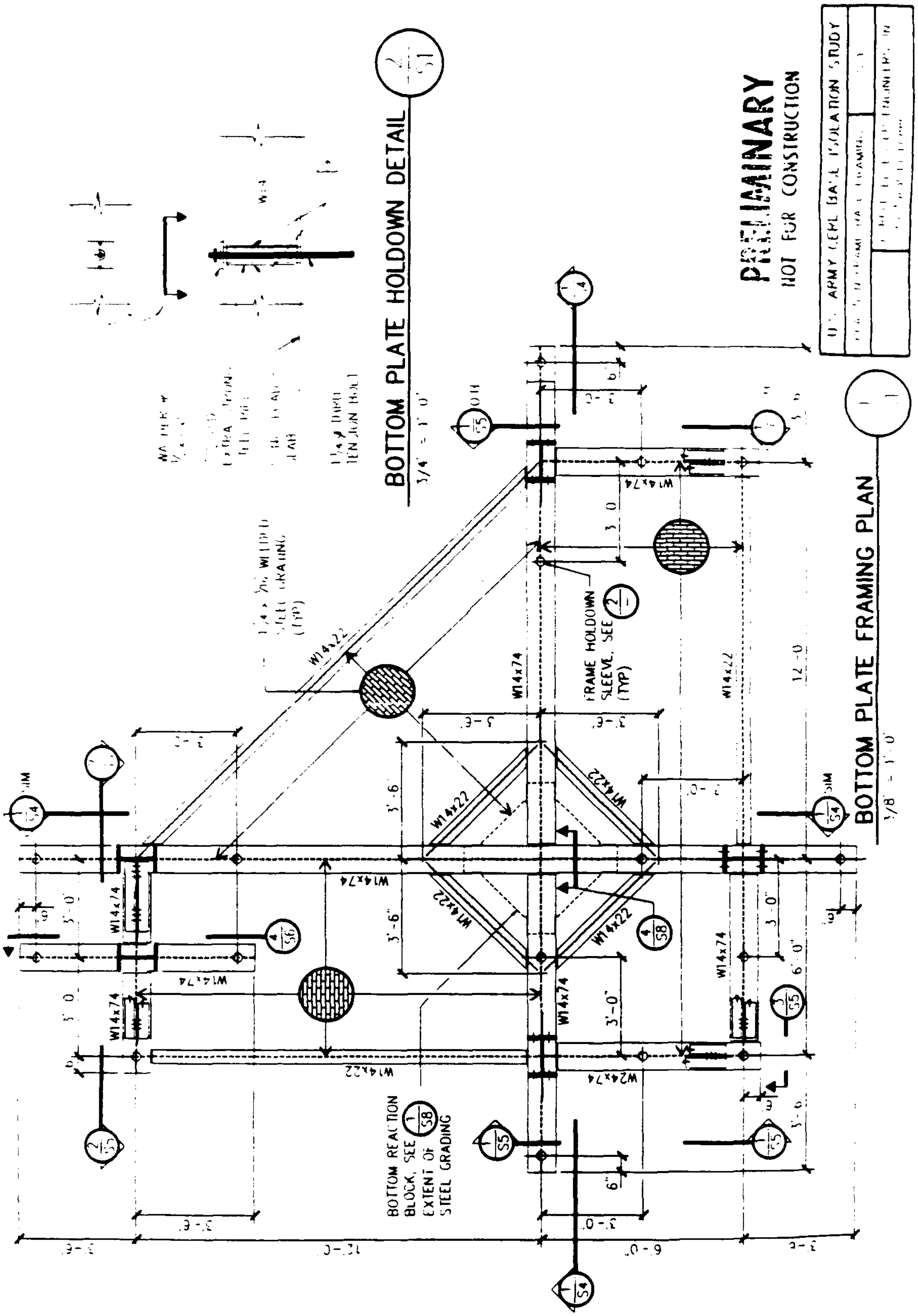
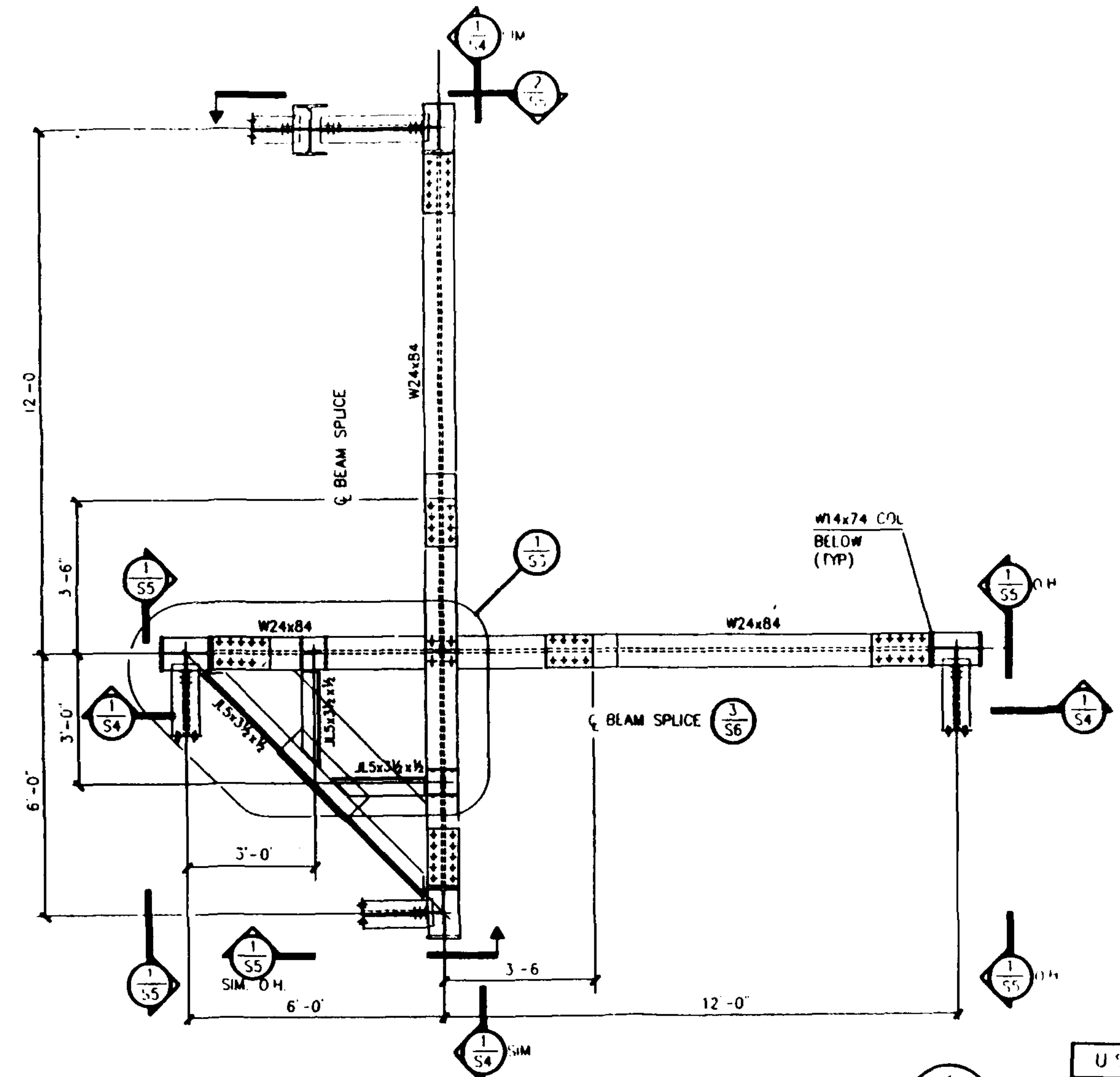
APPENDIX A: Construction Documents for Reaction Frame


BOTTOM PLATE HOLDOWN DETAIL
3/4" = 1'-0"
BOTTOM PLATE FRAMING PLAN
1/8" = 1'-0"
PRELIMINARY
NOT FOR CONSTRUCTION
FRAME HOLDOWN SLEEVE, SEE (TYP)
BOTTOM REACTION BLOCK, SEE
EXTENT OF STEEL GRADING
W14x74
W14x22
W24x74

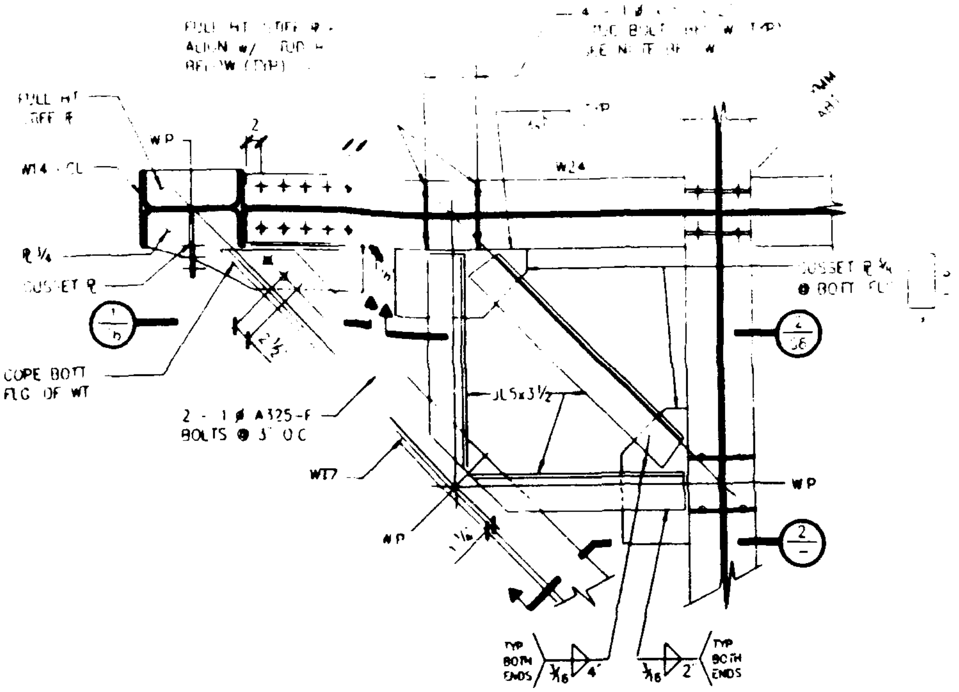


TOP PLATE FRAMING PLAN

SCALE 3/8" = 1'-0"

PRELIMINARY

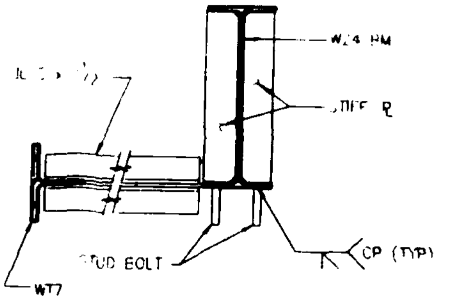
U.S. ARMY CERL BASE ISOLATION STUDY	
REACTION FRAME TOP FRAMING	
	FOPELLI/ELLESSER ENGINEERS INC Structural Engineers



NOTE VERIFY LOCATION AND SPACING OF STUD BOLTS WITH ACTUATOR SUPPLIER

DETAIL 1/S3

3/4" = 1'-0"



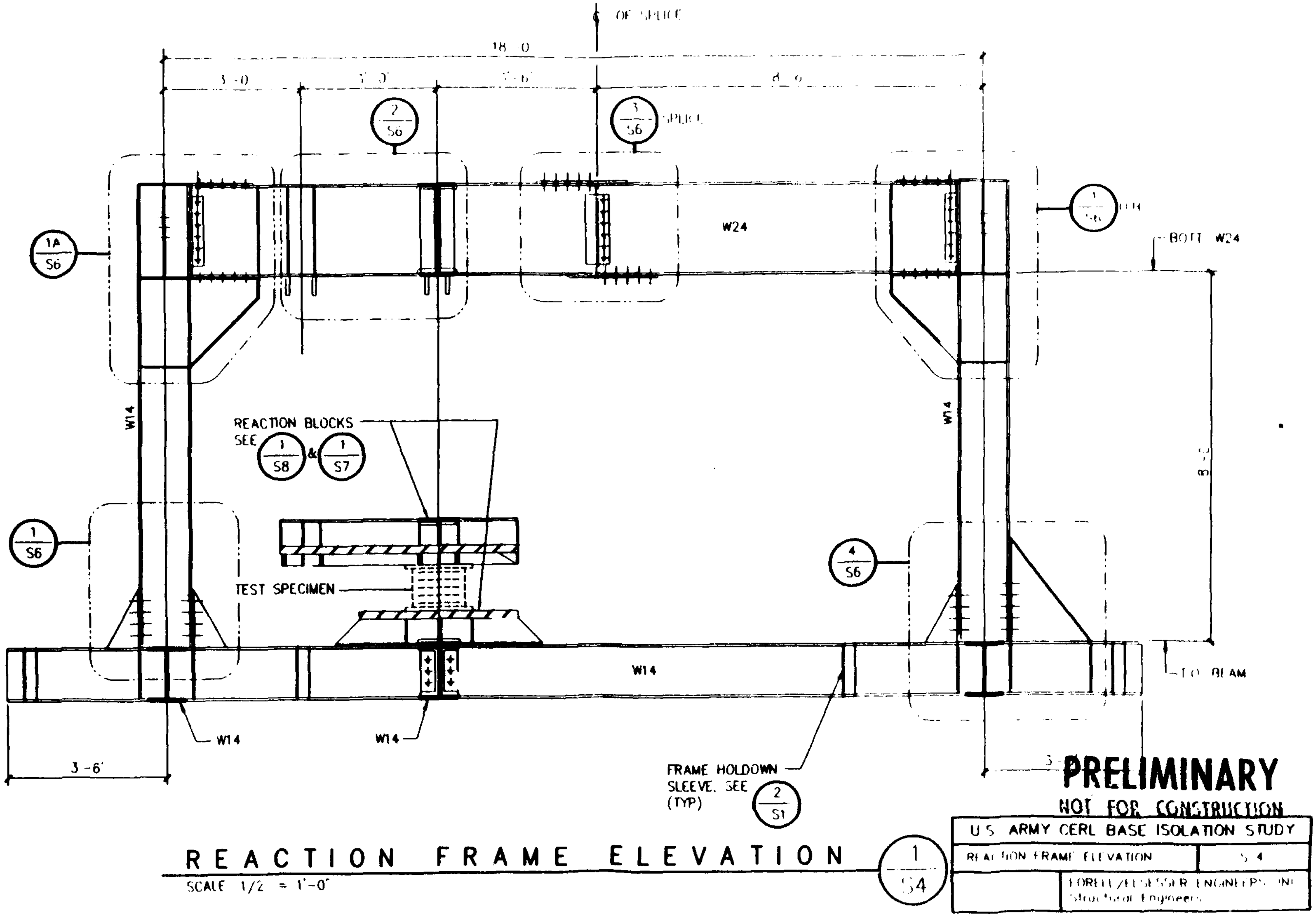
SECTION 2/S3

3/4" = 1'-0"

PRELIMINARY

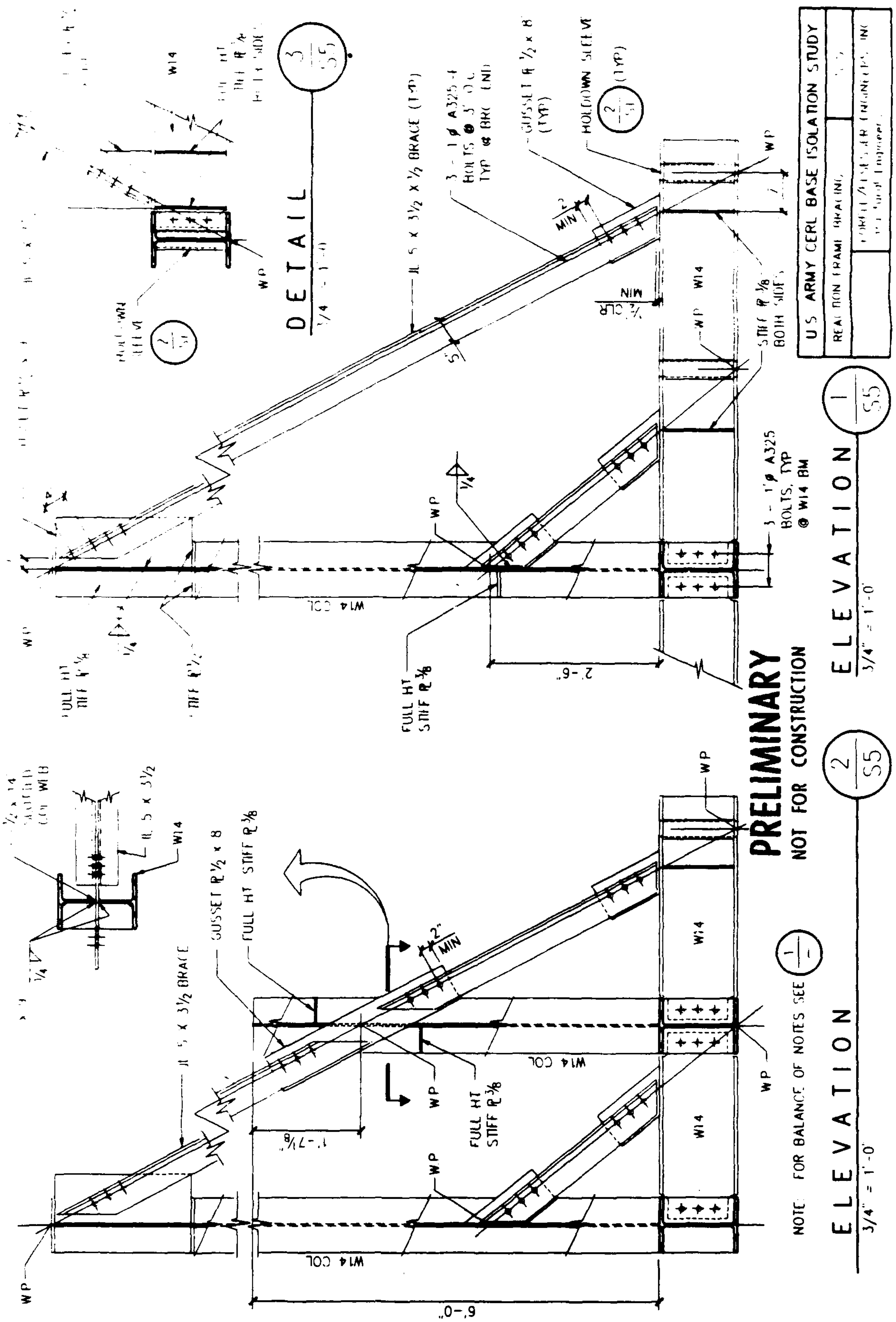
NOT FOR CONSTRUCTION

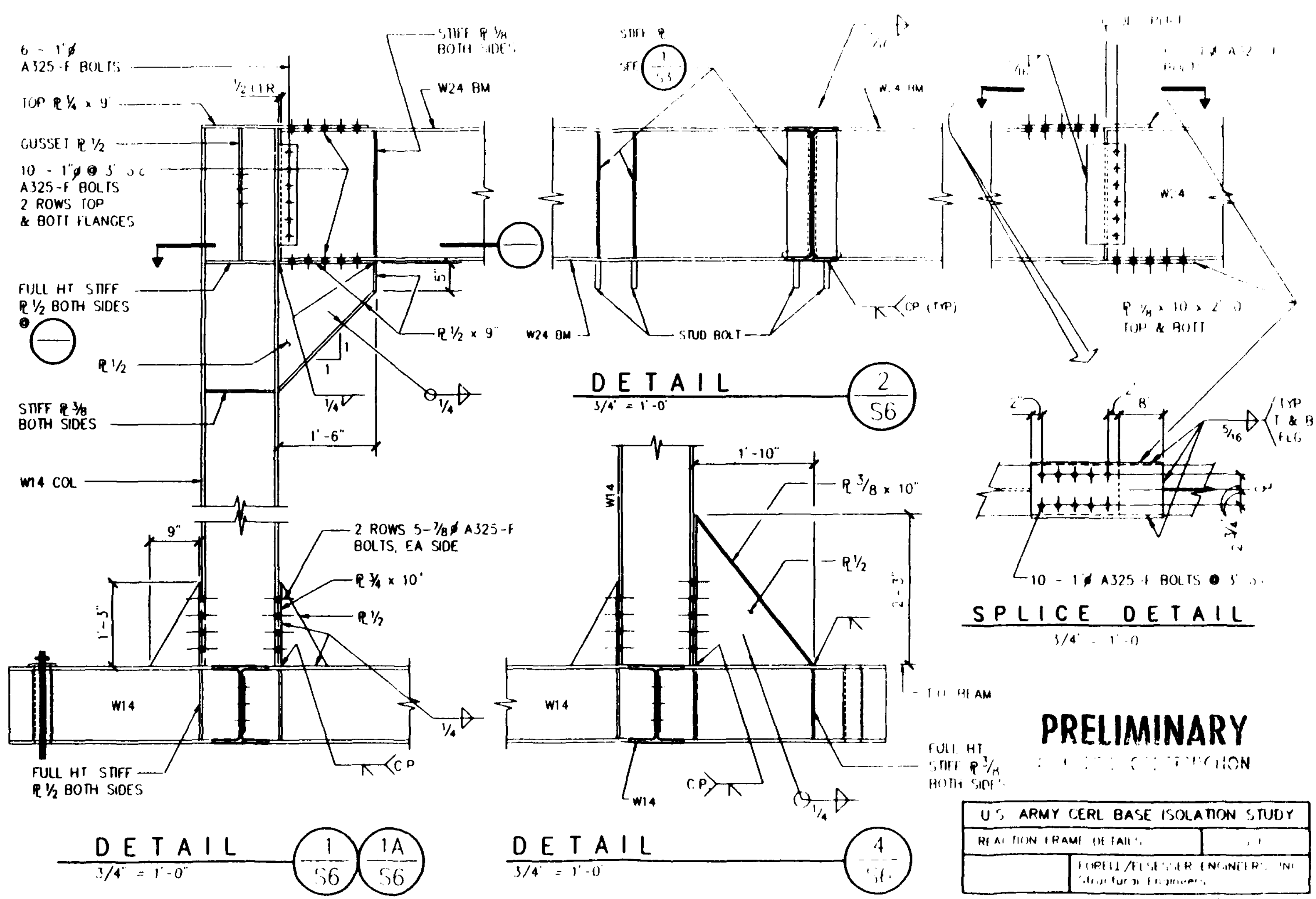
U.S ARMY CERL BASE ISOLATION STUDY	
TOP FRAME DETAILS	S 3
	FORELL/ELSESSER ENGINEERS, INC Structural Engineers



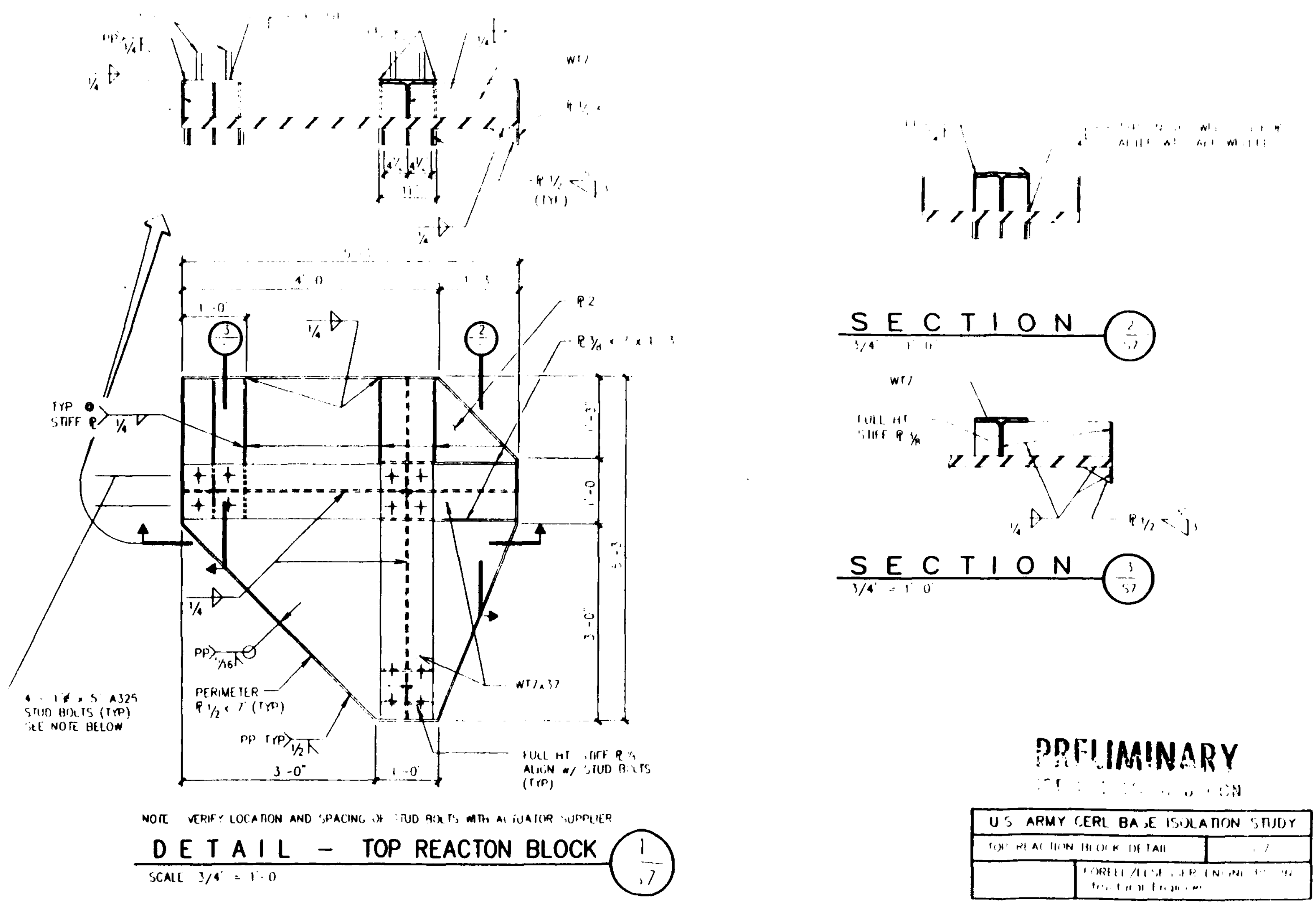
REACTION FRAME ELEVATION

SCALE 1/2" = 1'-0"

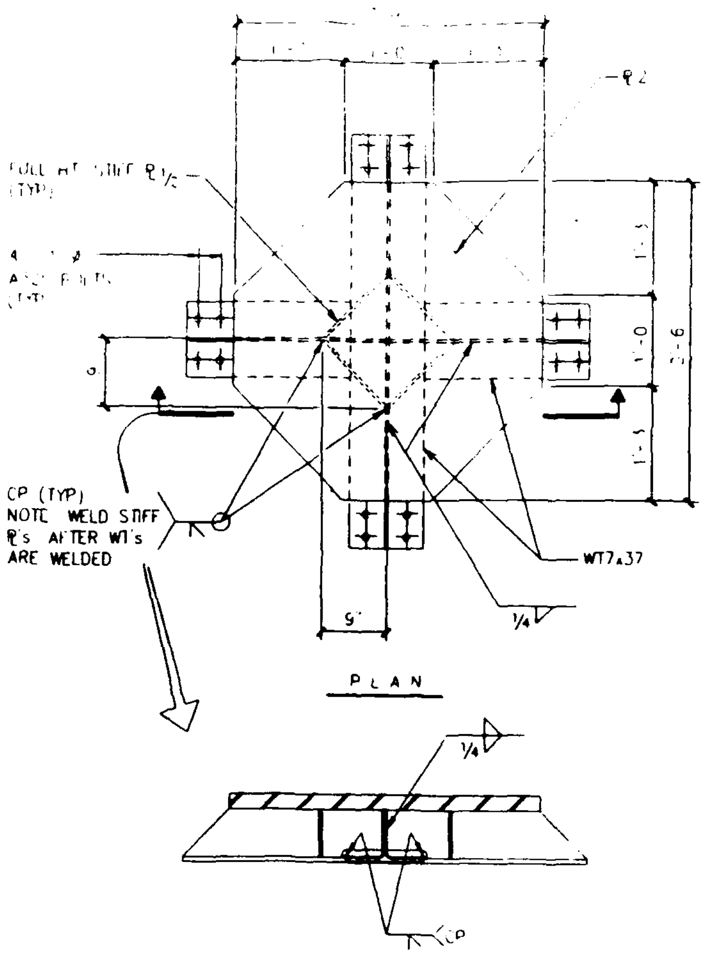

DETAIL
3/4" = 1'-0"
ELEVATION
3/4" = 1'-0"
ELEVATION
3/4" = 1'-0"
PRELIMINARY
NOT FOR CONSTRUCTION
NOTE: FOR BALANCE OF NOTES SEE
U S ARMY CERL BASE ISOLATION STUDY
JL 5 x 3½ x ½ BRACE (TYP)
3 - 1 ø A325 BOLTS, TYP @ W14 BM
GUSSET PL ½ x 8
FULL HT STIFF PL ⅜
HOLDOWN SLEEVE
STIFF PL ⅜ BOTH SIDES
W14 COL
W14
WP
2" MIN
2'-6"
1'-7⅞"
6'-0"



6 - 1"ø A325-F BOLTS
TOP ℞ ¼ x 9"
GUSSET ℞ ½
10 - 1"ø @ 3" o.c. A325-F BOLTS 2 ROWS TOP & BOTT FLANGES
FULL HT STIFF ℞ ½ BOTH SIDES
℞ ½
STIFF ℞ ⅜ BOTH SIDES
W14 COL
½" CLR
STIFF ℞ ⅜ BOTH SIDES
W24 BM
℞ ½ x 9"
1'-6"
9"
1'-5"
2 ROWS 5-⅞ø A325-F BOLTS, EA SIDE
℞ ¾ x 10"
℞ ½
W14
FULL HT STIFF ℞ ½ BOTH SIDES
CP
DETAIL
3/4" = 1'-0"
1 S6
1A S6
STIFF ℞
W24 BM
STUD BOLT
CP (TYP)
DETAIL
3/4" = 1'-0"
2 S6
℞ ⅜ x 10 x 2'-0 TOP & BOTT
W14
1'-10"
℞ ⅜ x 10"
℞ ½
W14
CP
DETAIL
3/4" = 1'-0"
4 S6
FULL HT STIFF ℞ ⅜ BOTH SIDES
TYP T & B FLG
5/16
8"
2"
10 - 1"ø A325-F BOLTS @ 3" o.c.
SPLICE DETAIL
3/4" = 1'-0
PRELIMINARY
U.S. ARMY CERL BASE ISOLATION STUDY
REACTION FRAME DETAILS
FORELL/ELSESSER ENGINEERS INC
Structural Engineers



WT7
TYP STIFF ℞ 1/4
4 - 1" x 5" A325 STUD BOLTS (TYP) SEE NOTE BELOW
℞ 2
PP 1/16
PERIMETER ℞ 1/2 x 7" (TYP)
PP TYP 1/2
3 -0"
1 -0"
4'-0
1'-0"
3'-0"
WT7x37
FULL HT. STIFF ℞ ALIGN w/ STUD BOLTS (TYP)
NOTE VERIFY LOCATION AND SPACING OF STUD BOLTS WITH ACTUATOR SUPPLIER
DETAIL - TOP REACTON BLOCK
SCALE 3/4" = 1'-0
SECTION
SECTION
FULL HT STIFF ℞ 3/8
SECTION
3/4" = 1'-0
PRELIMINARY
U S ARMY CERL BASE ISOLATION STUDY
TOP REACTION BLOCK DETAIL



DETAIL – BOTTOM REACTION BLOCK

SCALE 3/4" = 1'-0"

1 / S8

PRELIMINARY

NOT FOR CONSTRUCTION

U.S. ARMY CERL BASE ISOLATION STUDY	
BOTTOM REACTION BLOCK DETAIL	
	FORELL/ELSESSER ENGINEERS, INC. Structural Engineers

APPENDIX B: Base Isolation Vendors and Researchers Contacted About Comparative Testing Program

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Buffalo, New York 14260

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P.O. Box 6897
San Mateo, CA 94403

Professor Michael C. Constantinou
Department of Civil Engineering
State University of New York
212 Ketter Hall
Buffalo, New York 14260

Dr. Gilles Del Fosse
Residence La Bruyere, B2
13009 Marseilles, France

Mr. Fuzier
Freyssinet
Département Technique
52-54, Rue de la Belle Feuille
92100 Boulogne Billancourt
France

Mr. Edward Fyfe
Fyfe Associates
1341 Ocean Avenue
Del Mar, California 92014

Mr. Stephen Graves
International Industrial Rubber Products
Sales Department No. 1
Bridgestone Corporation
10-1 Kyobaski 1-Chrome
Chuo-ku, Tokyo 104
Japan

Professor James M. Kelly
Dept. of Civil Engineering, Davis Hall
University of California
Berkeley, California 94705

Dr. Ronald L. Mayes
Dynamic Isolation Systems, Inc.
2855 Telegraph Avenue, Suite 410
Berkeley, California 94720

Mr. Wayne Miller
Furon
Structural Bearing Division
FM 2495 Progress Way
P.O. Box 1580
Athens, Texas

Mr. Paul C. Rizzo
10 Duff Road, Suite 300
Pittsburgh, Pennsylvania 15235

Dr. Victor A. Zayas
Earthquake Protection Systems
1045 Sansome Street, Suite 203
San Francisco, California 94111

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ATTN: Library
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Washington, DC 20523-1436

Farmers Home Administration
Prog Support Staff Architect
Department of Agriculture
Washington DC 20250

Fac Engineering/Forest Service
ATTN: Library
Washington DC 20250

Architect of the Capital
Washington DC 20515

Bureau of Reclamation
ATTN: Library
Denver CO 80225

Department of Commerce
ATTN: Library
Washington DC 20230

National Inst. of Standards and Technology
ATTN: Library
Gaithersburg MD 20899

Chief of Engineers Office (04B2)
Department of the Navy
Alexandria VA 22322

Impact Aid Program
U.S. Department of Education
Washington DC 20202-6244

Department of Energy 20585
ATTN: Engr & Operations Support (DP 621 GTN)
ATTN: Nuclear Safety (NE 70)
ATTN: Risk Assessment and Tech (EH 33)

Office of Water Program Operations
Environmental Protection Agency
Washington DC 20460

Office of Earthquake and Other Natural Hazards
Federal Emergency Mgmt Agency
Washington DC 20472

Office of Design and Construction
General Services Administration
Washington DC 20405

Div of Health Fac Planning/ORM/OM
U.S. Public Health Services
Rockville MD 20857

Architectural Branch
U.S. Housing & Urban Development
Kansas City KS 66101-2406

Department of Housing and Urban Development 20410-8000
ATTN: Office of Housing Operations
ATTN: manufactured Housing & Constr Stds Div

U.S. Bureau of Reclamation
ATTN: W-6500
Washington DC 20240

U.S. Geological Survey
ATTN: Off. of Earthquake, Volcanoes & Eng 22092
ATTN: Denver Fed'l Center MS 966 80225

Department of Justice
ATTN: Library
Washington DC 20530

Federal Bureau of Prisons
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Department of Labor
Office of Construction and Engineering
Washington DC 20210

NASA Headquarters
Facilities Engineering Office/JX
Washington DC 20546

National Science Foundation 20550
ATTN: Earthquake Haz Mitigation Program
ATTN: Directorate for Engineering

Nuclear Regulatory Commission
Washington DC 20555

Office of Design & Construction
U.S. Postal Service
Washington DC 20260-6412

Office of Operations
Small Business Administration
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Office of Design & Construction
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Rosslyn Station VA 22209

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Earthquake Engr Research Ctr
University of California, Berkley 94804

Army Health Facilities Planning Agency
Falls Church VA 22041-3258

Air Force Health Facilities Office
San Francisco CA 94111-2217

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Defense Tech Info Center 22304
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